EXHIBIT DX1

TO DECLARATION OF
BENJAMIN W. HULSE IN SUPPORT
OF DEFENDANTS' MEMORANDUM IN
OPPOSITION TO PLAINTIFFS' MOTION
TO EXCLUDE TESTIMONY OF
THOMAS KUEHN, PH.D.

Expert Report: Thomas H. Kuehn, Ph.D.

In re Bair Hugger Products Liability Litigation

I am a mechanical engineer with extensive expertise in indoor environments, clean spaces, filtration and bioaerosols. I have been retained by 3M to provide opinions on matters pertaining to airflow and filtration concerning the Bair Hugger and its use in the operating room environment. I am being compensated at the rate of $250 per hour for my work in this case. I have not testified in any cases in the past four years.

1. Education and Experience

My complete CV is attached as exhibit A. My education includes a B.M.E. degree from the University of Minnesota in 1971 with High Distinction, and M.S. and Ph.D. degrees from the same institution with emphasis on natural convection heat transfer. I was a faculty member in the Mechanical Engineering Department at Iowa State University from 1976 to 1983. From 1983 until 2016 I was a faculty member in the Mechanical Engineering Department at the University of Minnesota. I served as the Director of the Environmental Division from 1997 to 2009 and the Director of Graduate Studies for the Mechanical Engineering and Industrial Engineering graduate programs from 1994 to 2000. At present I am a Professor Emeritus at the University of Minnesota.

I have taught many different courses in the mechanical engineering curriculum focusing on heating, ventilating and air conditioning (HVAC) topics. Course titles include “Thermodynamics”, “Thermal Environmental Engineering”, HVAC System Design” and “Vapor Cycle Systems”. I am the lead author on one of the few text books in that area (Thermal Environmental Engineering, 3rd ed., Prentice Hall). My main professional society affiliation for the past 25 years has been the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). I have served on several society level committees including the Research Administration Committee, Technical Council and the Conference and Exhibition Committee. I was the lead organizer and Technical Chair for the Annual Meeting held in St. Louis, June, 2016.

My research activity has been supported by numerous state and federal agencies, companies and consortia. I have collaborated with several faculty colleagues in the Particle Technology Laboratory, the School of Public Health and the Veterinary Diagnostics Laboratory, all at the University of Minnesota. Other collaborators include faculty at other universities, researchers at federal laboratories, and research personnel at corporate laboratories.

My initial work in the area of clean rooms began in the 1980’s under the sponsorship of the Particulate Contamination Control Research Consortium sponsored by several companies in the semiconductor manufacturing business. Both numerical flow simulations with airborne particle motion and experiments in semiconductor manufacturing clean rooms were performed. We published a challenge to researchers around the world in the IES Journal to submit their airflow and particle simulation results to us for comparison to measurements made in our Class 10 clean room.

The Center for Filtration Research was subsequently formed at the University of Minnesota to address issues associated with filtration of airborne particles. I have been affiliated with this Center since its founding. Much of my activity has addressed the filtration of bioaerosols including airborne bacteria, fungi and viruses. Additional support for this work has been provided by ASHRAE, NIOSH and corporations including Boeing. Capture efficiency of airborne particles versus filter type and filter loading, growth of captured particles on clean and loaded filters, and the influence of environmental parameters such as temperature, humidity and air flow rate were determined in laboratory settings, field trials or both.

Additional work on particles included a study to quantify particle removal from semiconductor wafers using megasonic cleaning. My laboratory has been very active over the past 20 years in characterizing the particle and vapor emissions from commercial cooking processes. This has resulted in new technologies being used to improve the capture of grease effluents in commercial kitchens and changes in emission regulations in the Los Angeles basin (South Coast Air Quality Management District) and the San Francisco Bay area (Bay Area Air Quality Management District).

I have worked with a group of students to design, build and operate a filter test facility that follows the requirements given in ASHRAE Standard 52.2. Our facility has extra capability for humidity control that is not included in the Standard. This facility has been used primarily to study the performance of building ventilation filters on bacteria, fungi and virus aerosols.

Students under my direction also designed, built and operated a ventilation test facility that has been used to study the movement of room air under a variety of conditions. This was designed to be operated as a one-half scale room. The supply air temperature, humidity and flow rate could be varied and the wall temperatures could be controlled separately to study the influence of combined forced and buoyancy-driven natural convection. Several air supply and exhaust configurations have been studied. Measurements in the chamber included thermocouples for temperature measurement, gas sampling probes and gas analyzers for tracer gas measurements, hot wire anemometers for velocity and turbulence measurements, and neutrally buoyant helium bubbles and water fog droplets for visualizing the air flow patterns. The chamber was also used to study the loss of infectivity of airborne virus particles as a function of room air temperature and humidity, time of flight between injection and recovery and the local UV intensity provided by UV lights installed in the upper corners of the chamber.

2. Review of Bair Hugger Filtration

I have reviewed the testimony of Karl Zgoda and Dr. Robert Crowder concerning the history of the filter media used in the Bair Hugger 500 and 700 series models. I have also reviewed test results from 3M regarding the minimum efficiency rating value ("MERV") for the filters currently used in all Bair Hugger models. It is my opinion that the Bair Hugger filters are effective at removing airborne bacteria from the air that passes through them and are therefore appropriate for use in the operating room as they provide an additional removal mechanism for airborne bacteria.

A. Filtration Concepts

Bair Hugger filters are made of fibrous media – strands of borosilicate glass fibers - arranged randomly into a mesh. Fibrous filters do not work like a sieve, with uniformly sized pores in a sheet of material that exclude particles larger than the pore size. Rather, they appear more like a bird's nest when viewed under a microscope. The majority of the volume is air with only a small percentage of the volume occupied by the fibers. Chemicals called binders are often used to hold the fibers together. Typical fiber diameter can range from about 20 microns down to a few nanometers. Here is a microscopic image of a glass fiber filter media:

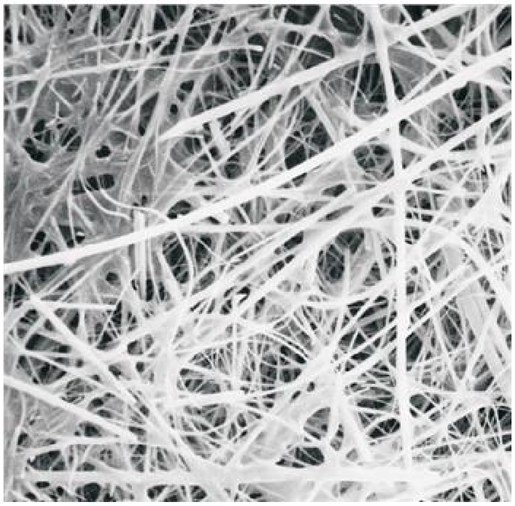

Fig. 1 Borosilicate Glass Matrix (Image from http://www.supplymylab.com/Supplies/Filter-Paper/_/PRESEP-GLASS-PREFILTERS?q=1215551&gclid=CLaC2YDBmNQCFQkIaQod3DMP7A)

Fibrous media trap particles through a combination of three mechanisms: interception, impaction, and diffusion. Interception occurs when a particle travels on a streamline close enough to a filter fiber to contact the surface of the fiber and stick to it.

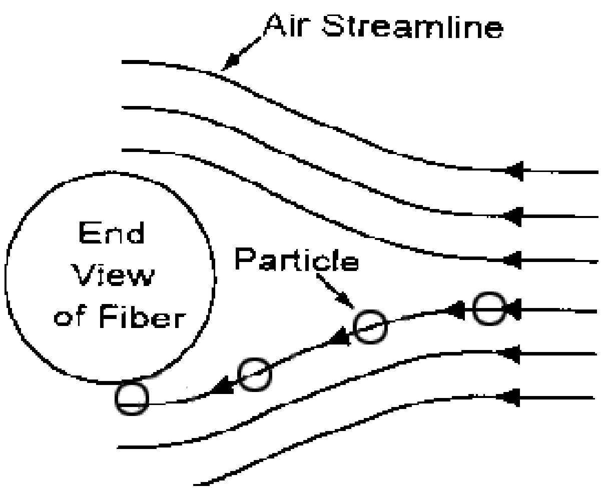

Fig. 2 Direct Interception (image from http://www.tsi.com/uploadedFiles/_Site_Root/Products/Literature/Application_Notes/ITI-041.pdf)

Impaction occurs when the momentum of a larger particle causes it to deviate from a streamline and collide with a filter fiber (rather than follow the streamline around it).

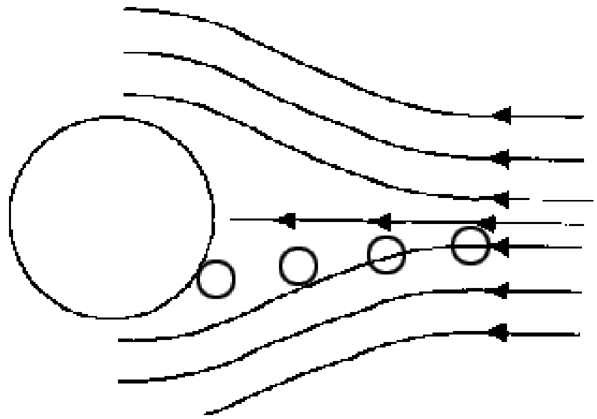

Fig. 3 Inertial impaction

Diffusion is important with very small particles (less than .1 um in size). Particles of this size constantly collide with air molecules, which causes them to travel in a random manner known as Brownian motion. This makes the particles susceptible to capture by dispersion to the fiber surface from their time averaged streamline.

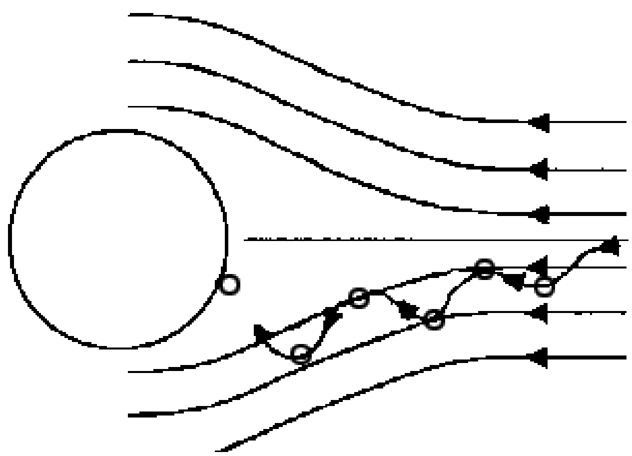

Fig. 4 Diffusion

Each of these three mechanisms plays a role in the filter's overall efficiency (its ability to capture particles of different sizes). Figure 5 shows the role that each mechanism plays at different particle sizes.

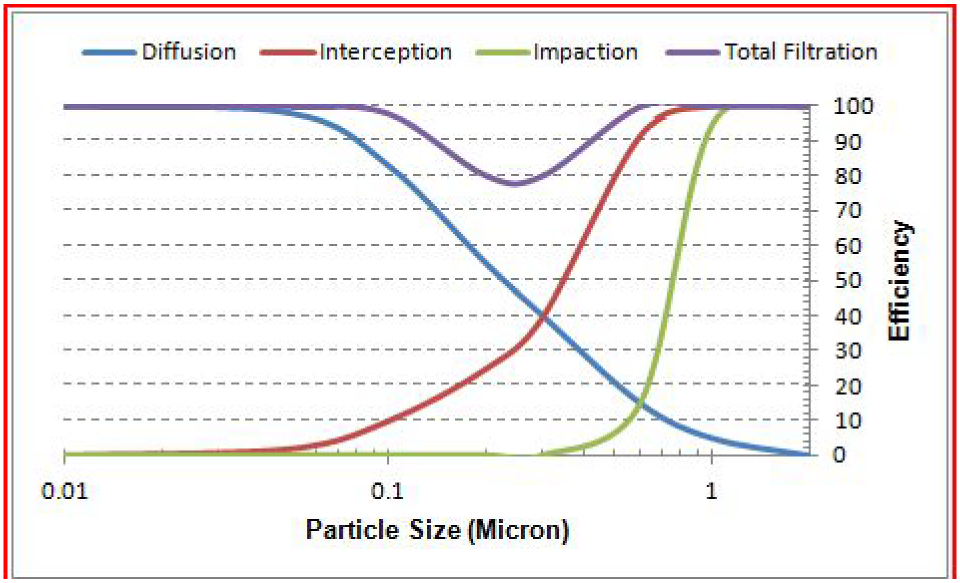

Fig. 5 Sample Filter Efficiency Curve for a Glass Fiber Filter

Figure 5 shows how the particle capture of a glass fiber media filter depends on particle size. The particle size is given in terms of aerodynamic diameter or the diameter of a particle with a density of 1 gm/cc. The results are also velocity dependent: if the mean velocity of the air that passes through the filter decreases, the minimum filter efficiency will increase. As Figure 5 shows, very small particles (less than .1 um) are captured primarily by diffusion, but diffusion drops off as particles gain size and mass. As particle sizes increase, interception and impaction play a greater role until they dominate the capture mechanism. The particles that the filter is least efficient at capturing are those that are too big to be completely captured by diffusion, but too small to be completely captured by interception or impaction. Thus, the efficiency curve for a glass filter will always dip at the "most penetrating particle size" or MPPS. The MPPS for this filter is in the range of .2-.3 microns. This aerodynamic particle size will always be the lowest point in a filter's efficiency curve (see purple curve in Fig. 5). All media filters have their most penetrating particle size in this size range as it is governed by particle physics, not the filter material or design.

The American Society of Heating, Refrigeration, and Air Conditioning Engineers ("ASHRAE") has developed a test method for determining the efficiency of filters used in HVAC systems and other related applications. The method was originally developed at Research Triangle Institute (RTI) by Jim Hanley under contract from ASHRAE. The test facility required in the Standard is similar to the one used at RTI. Potassium Chloride is used as the test aerosol as a high concentration polydisperse aerosol can be easily generated from a water solution using a nebulizer. The decision was made by the 52.2 Standards Committee to use an optical particle counter or OPC as the aerosol measuring instrument as it can provide real time aerosol concentration information versus particle size upstream and downstream of a test filter. By comparing the upstream and downstream results, the filter capture efficiency can be determined versus particle size.

An ASHRAE Standard 52.2 test facility was constructed in my laboratory at the University of Minnesota approximately 20 years ago. We included humidity control that was not specified in the standard so we could focus on filtration of bioaerosols. I served as the Principal Investigator for an ASHRAE contract to develop a Calibration Reference Device that would rely on first principles rather than calibrated optical particle counters to ensure that test facilities were in compliance with the Standard 52.2 requirements. Filters from the same lot had been sent to different test facilities with different test results so this project was an attempt to rectify this issue. Our design uses a three-stage parallel inertial impactor. The results of our project indicated that more work needed to be done to provide a reliable device at a cost that would be acceptable to the industry. At the present time, the originally specified 12 channel optical particle counters continue to be used at the filter test facilities.

Test method 52.2-2017 determines a filter's particle capture performance according to its ability to remove particles in three size ranges: 0.3-1 micron, 1-3 microns, and 3-10 microns. Test results will categorize the filter according to its Minimum Efficiency Reporting Value or "MERV". Figure 6 shows the MERV categories published in the 2017 version of the Standard:

Table 12-1 Minimum Efficiency Reporting Value (MERV) Parameters

Standard 52.2 Minimum Efficiency Reporting Value (MERV)	Composite Average Particle Size Efficiency, % in Size Range, μm			
	Range 1 0.30 to 1.0	Range 2 1.0 to 3.0	Range 3 3.0 to 10.0	Average Arrestance, %
1	N/A	N/A	$E_3 < 20$	$A_{avg} < 65$
2	N/A	N/A	$E_3 < 20$	$65 \le A_{avg}$
3	N/A	N/A	$E_3 < 20$	$70 \le A_{avg}$
4	N/A	N/A	$E_3 < 20$	$75 \le A_{avg}$
5	N/A	N/A	$20 \le E_3$	N/A
6	N/A	N/A	$35 \le E_3$	N/A
7	N/A	N/A	$50 \le E_3$	N/A
8	N/A	$20 \le E_2$	$70 \le E_3$	N/A
9	N/A	$35 \le E_2$	$75 \le E_3$	N/A
10	N/A	$50 \le E_2$	$80 \le E_3$	N/A
11	$20 \le E_1$	$65 \le E_2$	$85 \le E_3$	N/A
12	$35 \le E_1$	$80 \le E_2$	$90 \le E_3$	N/A
13	$50 \le E_1$	$85 \le E_2$	$90 \le E_3$	N/A
14	$75 \le E_1$	$90 \le E_2$	$95 \le E_3$	N/A
15	$85 \le E_1$	$90 \le E_2$	$95 \le E_3$	N/A
16	$95 \le E_1$	$95 \le E_2$	$95 \le E_3$	N/A

Fig. 6 MERV Parameters (ASHRAE 52.2-2017)

HEPA filtration, which tests filter efficiency at particles of 0.3 micron in size and smaller, is not covered by ASHRAE 52.2. For comparison with MERV numbers, HEPA filtration can be

assigned MERV numbers between 17 and 20, as shown in Fig. 7 taken from the 2007 version of ASHRAE Standard 52.2.

TABLE 2: MINIMUM EFFICIENCY REPORTING VALUE (MERV) PARAMETERS

ASHRAE Standard 52.2				ASHRAE Standard 52.1	Application Guidelines		
MERV	Particle Size Removal Efficiency, Percent in Particle Size Range, µm			Dust-Spot Efficiency Percent	Particle Size and Typical Controlled Contaminant	Typical Applications	Typical Air Filter/Cleaner Type
	0.3 to 1	1 to 3	3 to 10				
20	≥ 99.999	in 0.1 – 0.2 µm particle size		—	**< 0.3 µm** Virus (unattached) Carbon dust Sea salt All combustion smoke	Electronics manufacturing Pharmaceutical manufacturing Carcinogenic materials	HEPA/ULPA Filters*
19	≥ 99.999	in 0.3 µm particle size		—			
18	≥ 99.99	in 0.3 µm particle size		—			
17	≥ 99.97	in 0.3 µm particle size		—			
16	> 95	> 95	> 95	—	**0.3-1 µm** All bacteria Droplet nuclei (sneeze) Cooking oil Most smoke Insecticide dust Most face powder Most paint pigments	Superior commercial buildings Hospital inpatient care General surgery	**Bag Filters** – Nonsupported (flexible) microfine fiberglass or synthetic media, 12 to 36 inches deep. **Box Filters** – Rigid style cartridge, 6 to 12 inches deep.
15	85-95	> 90	> 90	> 95			
14	75-85	> 90	> 90	90-95			
13	< 75	> 90	> 90	80-90			
12	—	> 80	> 90	70-75	**1-3 µm** Legionella Humidifier dust Lead dust Milled flour Auto emission particles Nebulizer drops	Superior residential Better commercial buildings Hospital laboratories	**Pleated filters** –Extended surface with cotton or polyester media or both, 1 to 6 inches thick. **Box Filters** – Rigid style cartridge, 6 to 12 inches deep.
11	—	65-80	> 85	60-65			
10	—	50-65	> 85	50-55			
9	—	< 50	> 85	40-45			
8	—	—	> 70	30-35	**3-10 µm** Mold Spores Dust mite body parts and droppings Cat and dog dander Hair spray Fabric protector Dusting aids Pudding mix Powdered milk	Better residential Commercial buildings Industrial workplaces	**Pleated filters** –Extended surface with cotton or polyester media or both, 1 to 6 inches thick. **Cartridge filters** –Viscous cube or pocket filters **Throwaway** –Synthetic media panel filters
7	—	—	50-70	25-30			
6**	—	—	35-50	< 20			
5	—	—	20-35	< 20			
4	—	—	< 20	< 20	**> 10 µm** Pollen Dust mites Cockroach body parts and droppings Spanish moss Sanding dust Spray paint dust Textile fibers Carpet fibers	Minimum filtration Residential window air conditioners	**Throwaway** – Fiberglass or synthetic media panel, 1 inch thick. **Washable** – Aluminum mesh, foam rubber panel **Electrostatic** – Self-charging (passive) woven polycarbonate panel
3	—	—	< 20	< 20			
2	—	—	< 20	< 20			
1	—	—	< 20	< 20			

This table is adapted from ANSI/ASHRAE Standard 52.2-2007. [15]

**The last four MERV values of 17 to 20 are not part of the official standard test, but have been added by ASHRAE for comparison purposes. Ultra Low Penetration Air filters (ULPA) have a minimum efficiency of 99.999 percent in removing 0.3 µm particles, based on the IEST test method. MERVs between 17 and 19 are rated for 0.3µm particles, whereas a MERV of 20 is rated for 0.1 to 0.2 µm particles.*

*** For residential applications, the ANSI/ASHRAE Standard 62.2-2007*[16] *requires a filter with a designated minimum efficiency of MERV 6 or better.*

Fig. 7 MERV Parameters (with HEPA Ratings)

As Fig. 7 shows, filters with MERV parameters between 13 and 16 are considered appropriate for controlling all bacteria. The ASHRAE hospital HVAC design manual specifies MERV 14 filters for use in surgical suites. (HVAC Design Manual for Hospitals and Clinics, 2d Ed., p. 30 Table 2-4.)

B. Filtration of Bioaerosols

The filter's MPPS, which again is typically 0.2-0.3 microns, is not the relevant particle size for filtering bacteria and bacteria-carrying particles from air. Bacteria by themselves are much larger than 0.3 microns; for example, individual Staphyloccus bacteria are typically 0.8-0.9 microns in diameter. (Kowalski, W. J., W. P. Bahnfleth, T. S. Whittam (1999). "Filtration of Airborne Microorganisms: Modeling and Prediction." ASHRAE Transactions 105(2), 4-17, Table 1.) Further, Staph and other bacteria rarely travel in air as single organisms; typically they are clustered with other organisms, contained in water droplets, or attached to skin squames or dust particles. These particles are often several microns in size and are easily removed by filters in the MERV 13-16 range.

HEPA filtration is unnecessary for effective control of bacteria in air. Moreover, HEPA filtration can introduce a significant pressure drop and thereby cause more air to leak around the filter that can lead to increased passage of contaminated air compared to a MERV 14 filter. HEPA filtration will also increase the load on fan motors (because of the increased pressure drop compared with MERV 14 filters) and potentially increase maintenance costs and decrease their service life. As indicated above, the ASHRAE HVAC Design Manual for Hospitals and Clinics recommends MERV 14 filters for surgical suites, not HEPA filters.

C. The Bair Hugger Filters

Based on my review of deposition testimony and documents produced in this case, I understand that the Bair Hugger warming units incorporate a filter with media designated by the supplier, Pentair, as "M20." Arizant adopted this media for use in the Model 750 filters in the early 2000s, and in 2009 Arizant changed the media in its Model 505 filters from M10 to M20.

I have reviewed ASHRAE 52.2 test results from 3M that demonstrate that the filters incorporating the M20 filter media meet the requirements for MERV 14. I have seen no evidence that the efficiency of the M20 filter media has changed at all over the many years that 3M and Arizant have used it.

I understand that the filter media previously used by Arizant, M10, had greater efficiency in the 0.3-1 micron particle size range than the M20 media. As noted above, however, particles that carry infectious bacteria are generally larger than 1 micron. Further, the M20 media, at MERV 14, is fully capable of capturing bacteria and the particles that carry them. Thus, Arizant's switch from M10 to M20 media should not have made any difference in the Bair Hugger filters' capture of harmful pathogens.

Finally, I note that there are no ASHRAE standards for fan-blowing equipment used in operating rooms. The Bair Hugger's incorporation of a MERV 14 filter – the same minimum filtration level that ASHRAE recommends for air supplied to operating rooms – provides additional protection from airborne bacteria for patients undergoing surgery.

3. Comments on Plaintiffs' Expert Reports

Dan Koenigshofer

The majority of this report has been abstracted from the ASHRAE literature that provides design engineers guidance on the design of health care facilities. This is intended to be best practice and does not necessarily indicate how a particular facility has been designed or is operated.

On pages 20 and 21, calculations are presented that indicate that when the Model 505 Bair Hugger is operated, "at least 300 cfu/hr are blown near the patient." The initial room air concentration was estimated to be 10 cfu/ft^3 from a paper by Galson and Goddard from 1968. The purpose of this paper was to show the effect of different ventilation rates on indoor air concentration. This paper was published nearly 50 years ago and does not represent best current practice as given in the ASHRAE HVAC Design Manual for Hospitals and Clinics where room pressurization, filtration system performance and particle shedding from personnel are much better controlled. It is my professional opinion, that a room air concentration of 10 cfu/ft^3 would be considered extremely high for an OR that would use a Bair Hugger. The filter in a Bair Hugger would reduce the clean room air concentration even further before the air was sent to the blanket. Measurements of the air velocity and temperature that leave a Bair Hugger blanket were made and show that the room ventilation system is not significantly affected when the Bair Hugger is operated (Exhibit B). Thus the air is not blown near the patient. Neither are any bacteria particles that may become entrained by this air.

The following three statements have been made regarding particle motion and removal caused by the Bair Hugger:

1. The Bair Hugger operating in an OR will create turbulence at the floor, stirring settled particles.
2. The Bair Hugger draws particles off the floor into the unit. It functions much like a household vacuum cleaner.
3. The air velocity at the floor under the Bair Hugger is sufficient to entrain particles from the floor.

The Bair Hugger is provided with a feature that allows it to be attached to an IV pole. That allows the unit to be conveniently mounted approximately 18 to 24 inches above the floor so that the air velocity near the floor generated by the Bair Hugger is insignificant compared to the air velocity driven by the ventilation in the room, movement of personnel and the operation of other equipment.

Measurements of air velocity below a Model 775 Bair Hugger mounted approximately 2 ft above the floor indicated that there was no measurable difference between the air velocity near the floor when the Bair Hugger was off or turned on. Velocity measurements were also made at three

locations near the edge of the blanket where the warm air escapes into the room. None of these locations had air velocities large enough to affect the air velocity near the floor. Photos and data from these measurements are included in Exhibit B.

The manufacturer of the Bair Hugger also offers a cart to mount the unit on. When the Bair Hugger is used with this cart, the air velocity near the floor under the unit caused by the operation of a Bair Hugger is insignificant because the cart acts as a barrier between the bottom of the Bair Hugger unit and the floor.

The Bair Hugger can be placed on and operated from the OR floor. However, the maximum air velocity between the bottom of the Bair Hugger and the floor is much lower than what would be required to move or detach particles containing infectious bacteria sitting on the floor. The air velocity was measured between the bottom of a Bair Hugger and the top of a cart it was resting on to determine the velocity that would occur had the unit been sitting on a cart. The values between the bottom of the unit and a floor would be very similar. The velocity on all four sides was measured to determine the maximum value. Photos and the data recorded are provided in Exhibit B.

Using the maximum air velocity that was measured and published literature on particle motion and removal from surfaces, the results of calculations provided in Exhibit C clearly show that the physics do not support the three statements made that the Bair Hugger removes particles from the floor. The adhesion force between a hard sphere and the surface is much higher than the drag force created by the air velocity that could remove the particle. Bacteria would be more difficult to remove because they are not perfect spheres and have increased adhesion force caused by the increased contact area between the bacteria particle and the surface (Chuen-Jinn Tsai, David Y. H. Pui & Benjamin Y. H. Liu (1991) Elastic Flattening and Particle Adhesion, Aerosol Science and Technology, 15:4, 239-255). The measured maximum velocity is several orders of magnitude lower than what would be required.

The following statements have been made regarding air flow:

1. 50 -100 cfm are blown from the blanket into or near the sterile air field, causing air to move horizontally, while the intent of the HVAC system is to maintain downward air flow.
2. Air leaving the blanket at 100 to 110 F will cause upward convective air flow.
3. The hot air will lead to surgeon's discomfort, resulting in them requesting even lower temperatures in the OR.
4. The hot air from the Bair Hugger will interfere with the downward flow of clean air from the ceiling diffuser.

Air velocity measurements made near the hip of a manikin in a simulated OR configuration did not show any measurable difference when the Model 750 Bair Hugger was turned on at high fan speed or turned off. There was no measurable effect of the Bair Hugger operation on the air velocity. Photos and the measured data are given in Exhibit B.

The temperature of the air leaving the blanket and entering the room was measured to be less than 75º F when the room temperature was about 66º F and a model 750 Bair Hugger was operated at maximum flow rate and at high fan speed as shown in Exhibit B. The claim that the air leaves the blanket between 100 and 110º F was not substantiated. The much lower temperature as measured will not have a significant effect on the movement of the warm air leaving the blanket as shown in Exhibit D.

The temperature of the air measured at the location of the hip did not show significant difference between the time when the Bair Hugger was turned off and when it was turned on with a setting of 43 ºC, as shown in Exhibit B. It is unlikely that the surgeons would notice any difference in temperature, or any change in airflow as a result of temperature change.

The following statement was made regarding the cooling load in the OR:

1. The heater in the Bair Hugger adds to the cooling load, thus requiring more air and/or colder air than the initial design.

The energy consumed by a Bair Hugger is part of the cooling load in an OR along with all the other equipment and personnel. Typical design values for sensible thermal load for equipment in an OR are 1 kW. The Model 505 Bair Hugger uses approximately 528 W, the Model 750 480 W and the Model 775 390 W on the low setting and 470 W on the high setting. All of these are well within the estimated design value of 1000 W for equipment. As the Bair Hugger uses the power to provide heat, it may be the most energy intensive piece of equipment in the OR. It is unlikely that the total cooling load for all the equipment in an OR with a Bair Hugger operating would be larger than 1000 W. There would be no reason to increase the airflow rate over the design value when a Bair Hugger is used.

The equipment thermal load is not a very important portion of the cooling load in an OR. Tempering the outdoor ventilation air is the main load as shown by Figure 8.7 of Reference 1 where lights and equipment together are shown to be 10% of the total load. A good HVAC design should be able to accommodate slight variations in the design loads.

Changing the air flow rate in an occupied OR is not desirable as this may disrupt the pressure balance between the OR and adjacent areas. It is much better to adjust the supply air temperature using the reheat coil shown in Figure 8-4 of Reference 1 to handle variations in sensible cooling load while maintaining the desired humidity level.

The following statement was made regarding the filtration level in the Bair Hugger:

1. The filters in the Bair Hugger are less efficient than those used in the HVAC system serving an OR.

The recommended MERV for final filters used to clean incoming supply air to an OR is 14 (Reference 1). A 3M report documents the results of tests on the filters used in the Bair Hugger Model 775 to be MERV 14 (Reference 2). Thus the MERV recommended for OR supply air and the measured MERV for the filters used in Bair Hugger Model 775 are equal.

The actual performance of filtration systems in hospital air handling systems can vary widely. Leaks in the seals between the filter modules and the frame, punctures in the filter media that occur sometime between filter manufacture and installation, filters that become wet, and neglected maintenance can all result in less efficient filtration system performance than designed. Therefore the performance of a specific filtration system in a hospital or clinic is site dependent and cannot always be predicted by its design. Thus the general statement given above is not valid.

References

1. HVAC Design Manual for Hospitals and Clinics, 2nd ed., 2013, Section 8.
2. 3M report RD-Test-PW-05-286536, dated 8/25/2016, by Winston Tan

Said Elghobashi

This report contains the background and results of a numerical study of airflow and particle dissemination in an operating room with and without a Bair Hugger in operation near the floor. One of the underlying assumptions, the temperature of the air that leaves the Bair Hugger blanket, is not correct. A value of 106 F (41.1 C) is used when the temperature of the air supplied to the room was 59 F (15 C). Measurements made of the air leaving a Bair Hugger blanket provided in Exhibit B showed that the warmest temperature was 75 F when the temperature setting was 43 C (109 F) and the room temperature was about 66 F. The difference between the temperature of the air entering the blanket and leaving it is caused by the thermal transport to the patient (the purpose of the Bair Hugger) and the warming of the adjacent drapes. The actual measured temperature difference between the warm air leaving the blanket and the background room air temperature was 75 – 66 or 9 F rather than the assumed value of 106 -59 or 47 F. Thus the assumed thermal buoyancy of the warm air leaving the blanket is more than a factor of 5 too large as thermal buoyancy is linearly related to temperature difference. Correcting this error in boundary condition will result in airflow that does not change nearly as much when the Bair Hugger is operated as in the results presented.

There is no indication of particle removal by the filter in the Bair Hugger although that is another particle removal or air cleaning mechanism in the OR in addition to particles attaching to surfaces and leaving with the return air.

For the particle transport, 3 million particles 10 microns in size are assumed to reside within 1 cm of the floor. It is not clear why this region near the floor was targeted, the particles should follow the air currents in the room. Three areas are considered, only one results in particles being transported to what is termed the surgical box. These are colored red in the plots.

It is unclear how many particles are assumed to start from each of the three areas near the floor but most likely the three million particles were evenly distributed among the three areas so one million begin in each. As the red colored area is the only one that shows particles reaching the surgical box, particles in this area will be the only ones considered here.

The study could have used a different number of particles starting near the floor, for example 10 million or 100 million. That should increase the number reaching the surgical box by factors of 10 and 100 respectively. This does not mean that more particles will actually reach the surgical box area. The total number of particles reaching the box is not the important result, it is the fraction of particles that begin near the floor that reach the box.

Using the assumed value of one million particles that begin near the floor in the red area, they occupy a volume of 1.35m x 0.3m x 0.01m or 0.0041 cubic meters = 0.145 ft^3. The total mass of these particles using the density of 1 gm/cubic centimeter as stated in the report (unit density)

= (number of particles x density x 3.1415 x (particle diameter)^3)/ 6

$= ((10^6 \times (1\ gm/cm^3) \times 3.1415 \times (10 \times 10^{-6}\ m)^3)/6) \times (10^6\ \mu g/gm) \times (10^6\ cm^3/m^3)$

$= 524\ \mu g$

The particle mass concentration is this total particle mass divided by the volume of air they occupy:

Mass concentration = $524\ \mu g / 0.0041\ m^3 = 127{,}800\ \mu g/m^3$

As all the particles have a diameter of 10 μm, they are classified as a PM10 aerosol. This concentration is 852 times the current 24 hour daily maximum ambient National Ambient Air Quality Standard of 150 $\mu g/m^3$ for PM10 not to be exceeded more than once in a 3-year period. Thus this initial concentration used near the floor is several orders of magnitude higher than most unfiltered outdoor air. If a more realistic value is used, although a very conservative one, to assume that unfiltered, polluted outdoor air exists near the floor with a mass concentration of 150 $\mu g/m^3$, then the aerosol concentration results provided in this report should be adjusted accordingly.

For example, the results in Figure 31 where the red boxes are shown, the maximum number of approximately 560 should be divided by at least 852 resulting in a value less than 1.0. If very clean operating room air is assumed rather than polluted outdoor air, the resulting value becomes much lower than this. It is also very unlikely that all particles near the floor contain infectious bacteria. Therefore, it is very unlikely that any infectious particles residing near the floor in any of the three areas simulated will ever reach the critical care area.

Another method to estimate the number of culturable particles that might reach the critical care area is to assume a maximum value of 4 cfu/ft^3 in the initial red area based on concentration values given by Galson and Goddard (Reference 1) for general surgery areas. This value is from a publication nearly 50 years old so it is much larger than what one would expect today in a state-of-the-art OR so the present calculations show results much higher than what would be expected. The initial volume of the red box is 0.145 ft^3 so the total number of cfu initially in the box is:

Total cfu = 4 cfu/ft^3 x 0.145 ft^3 = 0.58 cfu

The number of these that might reach the critical area would be

Cfu-critical care = 0.58 cfu x 560/1,000,000 = 0.0003 cfu.

This is an extremely small value although as indicated above, is larger than what one would expect in a current well-maintained OR. In summary, the particle movement simulation results, if assumed to be correct, will not cause any significant contamination of the critical care area from particles located near the floor.

References:

1. Galson and Goddard, ASHRAE, 1968.

Michael Buck

This report is difficult to interpret because of a lack of clarity in the results. The plots presented have an undefined logarithmic scale on the vertical axis (that may be particle number counts) and appear to have a time scale on the horizontal axis. Several different conditions were tested but there is no indication of when each condition started and ended. Transients are evident between one condition and another when the results change with time. It is not known whether each test was performed for a sufficiently long period of time so that the transients do not influence the results. Buck did not replicate his tests. A minimum of three replicates at each condition is the norm for statistical accuracy. There are no blank test results showing particle counts with zero measurable particles entering the particle counter through one or more HEPA filters at the inlet so the background counts are unknown. The probe seems to be aligned with the air exiting the hose but that is not sufficient for isokinetic sampling. The mean velocity within the probe must be equal to the velocity in the surrounding air. There is no indication that this was considered. Using the same probe, the velocity within is fixed by the sampling pump in the instrument. However, the surrounding air velocity can vary depending on where the sample is taken. Without true isokinetic sampling, the particle concentration results can be biased.

It appears that total numbers of particles were measured. It is well known that the number concentration of particles increases dramatically as the particle size is reduced. This is shown on some of the figures. These particles are too small to contain bacteria.

No measurement of the nature of the particles was provided. Culture plates could have been used with an Andersen impactor or pour plates with an all glass impinger (AGI) to determine if any of the particles measured were culturable. Non-culturable particles collected on filters could have been analyzed for their chemistry to determine whether they originated from within the machine or simply passed through.

It is unclear from the figures when the filter was installed and when it had been removed so no definitive conclusion can be drawn regarding filter performance based on this report.

Yadin David, William Jarvis, Michael Stonnington

Each of these reports comments on Tsai et al., who provided some information on an event at MD Anderson Cancer center where a malfunction within an operating Bair Hugger caused black spots to be deposited on the skin of a patient and surroundings blankets. The black spots were assumed to be soot generated from an electrical malfunction within the unit and appeared to be

deposited near the location of holes in the blanket. I agree with Tsai's assessment that the particles were soot. However I disagree with the suggestion that the passage of soot particles through the Bair Hugger blanket provides evidence that pathogens can pass through the Bair Hugger system.

Soot particles are formed from a chemical reaction as illustrated in Figure 8. The particle formation begins as the molecular clusters grow into very small spherical particles about 20 nm in size. These in turn then aggregate to form chains that can be anywhere from about 30 to 40 nm in length to about 500 nm. A photo of two of these typical aggregate particles is shown in Figure 9 where the length scale bar in the lower left hand corner is 50 nm. The smaller of the two particles is about 70 nm in size whereas the larger one has a length of about 500 nm. The smaller particle has an aerodynamic diameter similar to its physical size because it is quite compact and roughly spherical in shape. The larger chain has an aerodynamic diameter much less than its length because it is much less dense and may be approximately 120 nm. The aerodynamic diameter of a particle determines its settling rate and how it behaves as it passes through a filter.

The soot particles that were observed to have deposited on the patient and surrounding blankets most likely were in the size range discussed above. Their aerodynamic diameter is much less than single bacteria spores and clumps of bacteria or bacteria attached to other material. Therefore the deposited soot is not a good indication that much larger bacteria particles would follow the same path and deposit similarly.

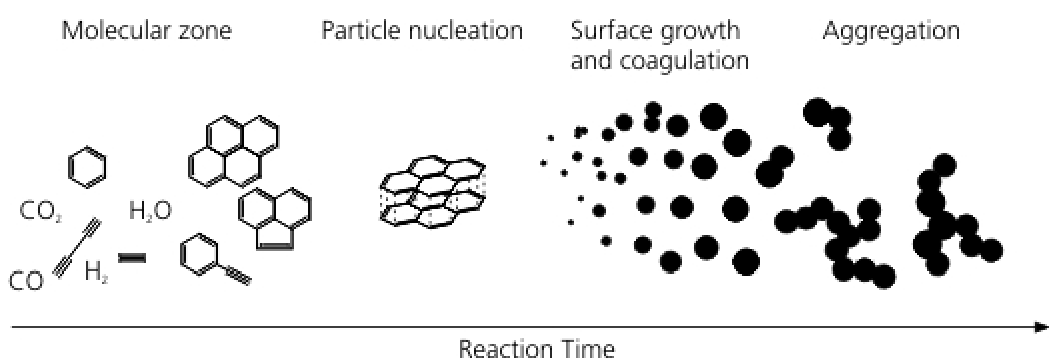

Fig. 8. Soot formation process.

http://www.forbrf.lth.se/english/research/measurement-methods/laser-induced-incandescence-lii/

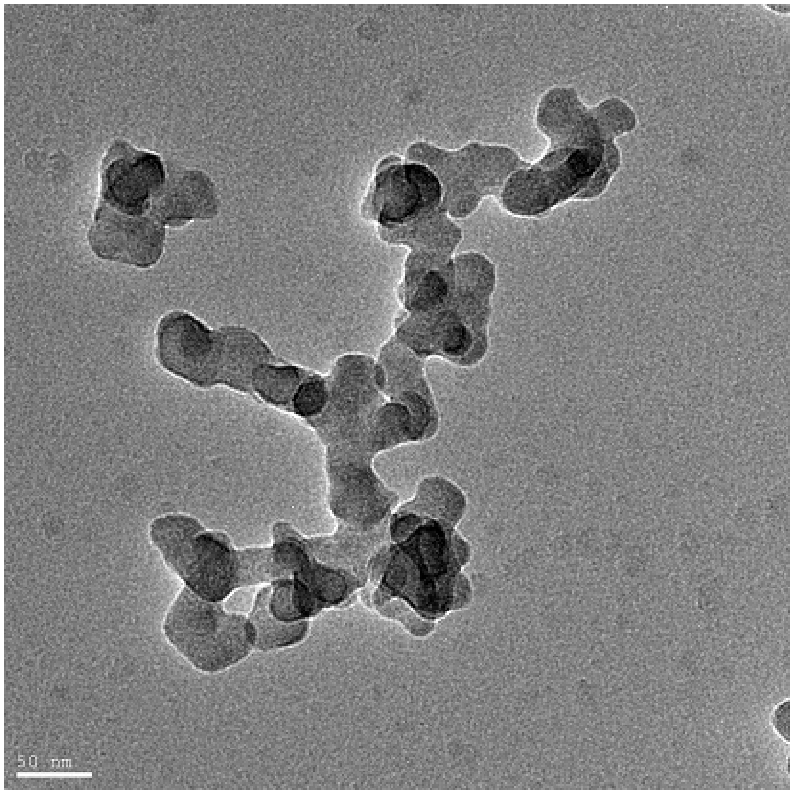

Fig. 9. Photo of agglomerated soot particles.

http://www.ltt.uni-erlangen.de/en/research/particle-measurement/

The materials I considered in my analysis are attached as Exhibit E. I reserve the right to supplement my analysis and provide additional opinions and observations in response to newly received information.

June 1, 2017

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Education

1971 B.M.E. with high distinction, University of Minnesota
1973 M.S. University of Minnesota
1976 Ph.D. University of Minnesota

Honors and Awards

Pi Tau Sigma, Tau Beta Pi, Sigma Xi
Young Mechanical Engineer of the Year 1983, Minnesota ASME
Excellence in Presentation of a Technical Paper, 8th International Heat Transfer Conference
Award of Excellence for a Technical Paper, 1989, Int. Appliance Technical Conference
Minnesota Supercomputer Institute, Associate Fellow 1994, Fellow 1998
Best Poster Awards, ASHRAE Meetings, Chicago, 1995 and San Antonio, 1996.
ASHRAE Transactions Paper Award, 2010.
Fellow ASME, 1997
Fellow ASHRAE, 2004
Distinguished Service Award, ASHRAE, 2015
E.K. Campbell Award, ASHRAE, 2017

Academic Experience

1976-1981	Assistant Professor, Department of Mechanical Engineering, Iowa State University
1981-1983	Associate Professor, Department of Mechanical Engineering, Iowa State University
1983-1990	Associate Professor, Department of Mechanical Engineering, University of Minnesota
1990-2016	Professor, Department of Mechanical Engineering, University of Minnesota
2016-present	Professor Emeritus, Department of Mechanical Engineering, University of Minnesota
1994-2000	Director of Graduate Studies, Mechanical and Industrial Engineering graduate programs, University of Minnesota
1997-2009	Director of Environmental Division, Department of Mechanical Engineering, University of Minnesota

Recent Service Activities

2002-2007	Research Safety Officer, Department of Mechanical Engineering, University of Minnesota
2003-2006	IT Representative to the University of Minnesota Writing Consultants Committee
2005-2006	Member of the University of Minnesota Presidential Committee on Undergraduate Writing
2010-2011	Chair Departmental Graduate Education Committee
2011-2012	Member of two Departmental faculty search committees
2012-2013	Member of Departmental Teaching Strategy Committee
2013-2015	Member of Departmental Promotions and Tenure Committee, Chair 2015

Selected Consulting Experience

2017-present	Blackwell Burke P.A.
2013-present	CaptiveAire
2009-2010	CaptiveAire
2005	Meagher & Geer P.L.L.P.
2005	Honeywell, Inc.

2004-2005	Varidigm, Inc
2004	Tetra Pak, Inc.
2001-2002	Phillips Plastics Corp.
2000-2001	State of Minnesota Board of Architecture, Engineering, Land Surveying, and Landscape Architecture
2000	Center for Energy and Environment
1998-2000	McQuay International
1994	Auto Vend, Inc., Brooklyn Center, MN
1993	District Energy, St. Paul, MN
1992	Wold Architects, St. Paul, MN
1987	EcoPure, Inc., Maple Grove, MN
1987-1990	Rochester Meat and Provision Co., Rochester, MN

Patents
U.S. Patent 4,555,764, November 26, 1985
Net energy transfer measurement methods, apparatus and systems with solar energy and control applications.

U.S. Patent 8,316,955, November 27, 2012
SAAR, Martin O., RANDOLPH, Jimmy Brian, KUEHN, Thomas H.
Carbon Dioxide-Based Geothermal Energy Generation Systems and Methods Related Thereto

U.S. Patent 8,833,475, 16 Sep 2014
Carbon dioxide-based geothermal energy generation systems and methods related thereto, Martin O. Saar, Jimmy Bryan Randolph and Thomas H. Kuehn

The following patents were received from foreign countries with the same inventors and title as the U.S. patent above:

Italy Patent 502015902338665, 20 Nov 2014,

Iceland Patent 2406562, 20 Nov 2014,

United Kingdom Patent 2406562, 20 Nov 2014

France Patent 2406562, 20 Nov 2014

Germany Patent 2406562, 20 Nov 2014

Netherlands Patent 2406562, 20 Nov 2014

Norway Patent 2406562, 20 Nov 2014

Switzerland Patent 2406562, 20 Nov 2014,

Turkey Patent 2406562, 20 Nov 2014

Australia Patent 2010223059, 27 Nov 2014

European Patent Office Patent 2406562, 17 Dec 2014

Hungary Patent 2406562, 17 Dec 2014

Professional Society Membership
American Society of Mechanical Engineers
American Society of Heating, Refrigerating and Air Conditioning Engineers

Community Service
Representative of the City of Mahtomedi on the White Bear Lake Conservation District Board, 1986-1989
President, Williams Woods Park Association, 2007-2011

Professional Activities

ASME
Chairman of organizing committee for Symposium Honoring Professor Richard J. Goldstein, ASME 2013 Summer Heat Transfer Conference, Minneapolis, July 15, 2013.

Member of *ASME* National Committee K-19, Environmental Heat Transfer 1982-1996

Chairman of *ASME* National Heat Transfer Visualization Committee, 1989-1992

Session Chairman, "Natural Convection in Stratified Flows," 23rd *ASME/AICHE* National Heat Transfer Conference, Denver, August, 1985

Session Chairman, "Heat Transfer in Buildings and Structures," 1987 National Heat Transfer Conference, Pittsburgh, August, 1987

Session Chairman, "Heat Transfer in Stratified Flows," 1988 National Heat Transfer Conference, Houston, July, 1988

Session Chairman, "Heat and Mass Transfer in Buildings and Structures," ASME Winter Annual Meeting, San Francisco, December, 1989

Session Co-Chairman, "Heat and Mass Transfer with Alternative Refrigerants," 1993 National Heat Transfer Conference, Atlanta, GA, August, 1993.

Secretary, Minnesota Section *ASME,* 1986-1987

Treasurer, Minnesota Section *ASME,* 1987-1988

Vice Chairman, Minnesota Section ASME, 1988-1989

Chairman, Minnesota Section ASME, 1989-1990

Director, Minnesota Section ASME, 1990-1992

ASHRAE
Technical Chair ASHRAE Annual Meeting, St. Louis, MO, June, 2016

Member Conference and Expositions Committee, 2012-2016
- Track Chair for all Research Summit sessions, Atlanta Meeting, June, 2015
- Track Chair for eleven IEQ sessions, New York Meeting, Jan 2014
- Track chair for all IEQ sessions, Seattle Meeting, June 2014

Appointed by Technical Council to Position Document Committee “Air Filtration and Cleaning”, 2012-2014.

Member Technical Council, 2008-2010.

Member Research Administration Committee, 2001-2005.

Chair of Committee to Revise Chapter 1, "Thermodynamics and Refrigeration Cycles", ASHRAE Handbook of Fundamentals, 1997 Ed. for TC 1.1, 1995-1996 and 2005 Ed., 2003-2004.

Chair of Committee to Revise Chapter 6, “Psychrometrics”, ASHRAE Handbook of Fundamentals, 2001 Ed. for TC 1.1, 1999-2000 and 2005 Ed., 2003-2004.

Chairman of ASHRAE National Technical Committee TC1.1, Thermodynamics and Psychrometrics, 1996-2000, Handbook Subcommittee Chair 2000-2005, Member or Corresponding Member1984-present

Member or Corresponding Member of ASHRAE National Technical Committee TC1.2, Instrumentation and Measurements, 1985-2002, Chairman of Research Subcommittee, 1990-2000

Member of ASHRAE National Technical Committee TC2.4, Particulate Air Contaminants and Particulate Contaminant Removal Equipment, 1995-present

Corresponding Member of ASHRAE National Technical Committee TC4.4, Thermal Insulation and Moisture Retarders, 1984-present

Session Chairman, "Refrigerant Thermodynamic Property Needs," ASHRAE Semi-Annual Meeting, Portland, June, 1986

IES&T

Session Co-Chairman, "Particle Generation and Control in Clean Rooms," Institute of Environmental Sciences 34th Annual Technical Meeting, King of Prussia, PA, May, 1988

Session Chairman, "Cleanroom Design and Control, " Institute of Environmental Sciences 36th Annual Technical Meeting, New Orleans, LA, April, 1990.

Session Chairman, "Air Flow Modeling: Theory," Institute of Environmental Sciences 37th Annual Technical Meeting, San Diego, CA, May, 1991.

Session Co-Chairman, "Computer Applications to Contamination Modeling," Institute of Environmental Sciences 37th Annual Technical Meeting, San Diego, CA, May, 1991.

Session Chairman, "Computer Applications to Contaminant Modeling," Institute of Environmental Sciences 38th Annual Technical Meeting, Nashville, TN, May, 1992.

Session Chairman, "Modeling, Particle Transport, Deposition and Removal," Institute of Environmental Sciences 39th Annual Technical Meeting, Las Vegas, NV, May, 1993.

Others

Session Co-Chairman, "Cleanrooms," American Association for Aerosol Research 1989 Annual Meeting, Reno, NV, October,1989

Session Co-Chairman, "Gas Cleaning," American Association for Aerosol Research 1990 Annual Meeting, Philadelphia, June, 1990.

Session Chairman, "Validation of Models, Ventilation Efficiency." Roomvent '94, Crakow, Poland, June 15-17, 1994.

University of Minnesota's Representative to Midwest Universities Energy Consortium, Inc., 1992-2002.

Session Chairman, “Bio-Aerosol Filtration,” 10th Annual National Technical Conference of the American Filtration & Separations Society, Minneapolis, MN, April 29-May 2, 1997.

Session Chairman, “Environment & Health,” 1999 Fall Topical Conference of the American Filtration & Separations Society, Minneapolis, MN, October 20-21, 1999.

Member awards committee AAAR, 2011-2013.

Invited Lectures

Department Mechanical Engineering, Illinois Institute of Technology, September 11, 1984.

Minnesota Department of Energy and Economic Development, Minnesota Radon Research Forum, January 18, 1985.

Minnesota Department of Energy and Economic Development, Safe Combustion Heating in Tightly Weatherized Homes, May 8, 1985.

Minnesota Engineering Society, July 15, 1985.

Workshop on Clean Technology, European Aerosol Conference, Lund, Sweden, September 2, 1988.

Chalmers Institute of Technology, Gothenburg, Sweden, September 5, 1988.

Nanjing Aeronautical Institute, Nanjing, China, September 11-17, 1988.

9th International Heat Transfer Conference, Jerusalem, Israel, August 19-24, 1990.

Nordic Institute for Advanced Training in Occupational Health, Copenhagen, Denmark, September 24-28, 1990.

ASHRAE Education/Energy Seminar, February 26, 1991.

Tutorial on Numerical Modeling of Particle Transport in Turbulent Flow, American Association for Aerosol Research Annual Meeting, October 7, 1991.

Presented a review of recent research, "Current Research Projects in Indoor Air Quality," with J. Ramsey, Winter Quarter MnBRC Lecture, University of Minnesota, March 5, 1992.

University of Duisburg, Duisburg, Germany, June 6 and 7, 1994.

"Air Flow Simulations in Microelectronic Clean Rooms", Industrial Design Corp., Portland, OR, May 11-12, 1995.

"Commercial Cooking Effluent Measurement Procedures", International Facility Management Association, Houston, TX, October 30-31, 1995.

"Microcontamination Measurements and Modelling in Clean Rooms", Twin Cities Chapter Institute of Environmental Sciences, Bloomington, MN, March 28, 1996.

"Experimentally Validated Modeling of Megasonic Cleaning Baths", Santa Clara Plastics Third International Symposium, Boise, ID, May 2-4, 1996.

"Studies of Room Air Motion and Contaminant Transport in Clean Rooms and Offices", Korea Institute of Science and Technology, Seoul, Korea, July 30, 1996.

"Room Air Flows in Clean Rooms and Offices", Pusan National University, Pusan, Korea, July 31, 1996.

"Innovative Applications for Sensors in Buildings", Honeywell Technology Center, Plymouth, MN, August 30, 1996.

"Recent Research on Microcontamination Measurements and Modelling ", Twin Cities Chapter Institute of Environmental Sciences, Bloomington, MN, April 10, 1997.

“Commercial Cooking Research at the University of Minnesota,” Commercial Kitchen Ventilation Seminar, Minneapolis, MN, November 3, 1997.

“Physical Mechanisms of Particle Removal from Silicon Wafers by Megasonic Energy”, Materials Research Society Spring Meeting, San Francisco, CA, April 7, 1999.

“Research Applied to Buildings at the University of Minnesota: a Brief Review”, Installationsteknik, Kungl Tekniska Hogskolan, Stockholm, Sweden, September 18, 2000.

“Filtration Research at the University of Minnesota”, Camfil-Farr, Trosa, Sweden, September 25, 2000.

“Recent Aerosol Research at the University of Minnesota”, Arbetslivsinstitutet/Arbetarskyddsstyrelsen, Stockholm, Sweden, November 10, 2000.

“Research on HVAC at the University of Minnesota”, Flakt ABB, Jonkoping, Sweden, November 29, 2000.

“Research on HVAC at the University of Minnesota”, ABB Ventilation Products AB, Division Stratos, Enkoping, Sweden, December 1, 2000.

“Bioaerosol Research at the University of Minnesota”, Pharmacia, Stockholm, Sweden, December 12, 2000.

“Particle Transport by Combined Natural Convection, Thermophoresis and Gravitational Settling”, Installationsteknik, Kungl Tekniska Hogskola, Stockholm, Sweden, December 15, 2000.

“Commercial Kitchen Research at the University of Minnesota”, Greenheck Fan Corporation, Schofield, WI, February 12, 2002.

“Enhancement of Natural Convection Heat Transfer from Horizontal Heat Exchanger Tubes”, First Bergles Symposium, Iowa State University, Ames, IA, October 17, 2003.

“Bioaerosol Filtration Research at the University of Minnesota”, DuPont Filtration R&D group, Richmond, VA, October 28, 2005.

“HVAC Research at the University of Minnesota”, Minnesota Chapter of ASHRAE, Golden Valley, MN, December 13, 2005.

“Issues with Microbial Filtration”, Phillips Plastics Corporation, Technology Center, Prescott, WI, February 15, 2006.

“Thermal Convection-Particle Interactions”, International Workshop Dust Storms, Erosion, Hurricanes and Tornadoes, Xi’an Jiaotong University, Xi’an, China, July 16, 2007.

“Bioaerosol Measurements in Airports and Aircraft Cabins”, First Boeing Company Workshop on Infectious Disease Transmission, Seattle, WA, October 6, 2011.

"Effects of Temperature, Humidity and Air Flow on Fungal Growth on Loaded Ventilation Filters", Filtration 2012, Philadelphia, PA, November 13, 2012.

"PM 2.5 Emissions from Cooking", 1st University of Minnesota-Chinese Academy of Sciences Bilateral Seminar on PM 2.5 Science, Health Effects and Control Technologies, Xi'an, China, May 27, 2014.

Research Support

Natural Convection Heat Transfer From a Single Row of Horizontal Cylinders in a Rectangular Enclosure, Iowa State University Research Foundation Research Initiation Grant, 1977.

Liquid-Heating Solar Collector Test Stand Development and Study of a Compound Parabolic Concentrator, Iowa State University Engineering Research Institute, 1977.

Laminar Flow and Heat Transfer in a Horizontal Rectangular Channel with One Heated Porous Wall, National Science Foundation Research Initiation Grant, 1978.

Experimental Evaluation of Above and Below Grade Wall Heat Transfer in the Iowa State University Energy Research House, Iowa State University Engineering Research Institute, 1978.

Enhancement of Heat Transfer by Natural Convection from Arrays of Horizontal Cylinders Immersed in Liquids, National Science Foundation, 1980.

Innovative Receiver Design for Parabolic Trough and Paraboloidal Dish Solar Collectors, U.S. Department of Energy, 1983.

Prediction and Measurement of Indoor Moisture Concentration in Occupied Buildings, University of Minnesota Graduate School Research Initiation, 1983.

Conjugate Natural Convection Heat Transfer from Horizontal Heat Exchanger Tubes, National Science Foundation, 1984.

Indoor Air Quality and Moisture Control in Buildings, State of Minnesota, 1984 (with J. Ramsey).

Theoretical and Experimental Studies of the Performance of Clean Rooms, IBM, Inc., Essex Junction, VT, 1985 (with B. Liu and J. Ramsey).

Fundamental Study of Purge Air System, Rosemount, Inc., 1985 (with D. Pui).

Studies on Clean Rooms, Vacuum Processing and Aerosol Sampling, Particulate Contamination Control Research Consortium, 1985-present (B.Y.H. Liu et al.).

Optimization of Rosemount Pyrometer Under Field Conditions, Rosemount, Inc., 1986, (with D. Pui).

Energy and Indoor Environment, State of Minnesota, 1987-1994 (with J. Ramsey).

Dust Collector Recirculation for Industrial Operations, American Society of Heating, Refrigerating and Air Conditioning Engineers, 1987 (with D. Pui).

Simulation of Moisture Movement and Storage in Buildings, State of Minnesota, 1988-1994 (with J. Ramsey).

Matching Filtration to Health Requirements, Phase I, American Society of Heating, Refrigerating and Air Conditioning Engineers, 1989-1990 (with D. Pui and D. Vesley).

Matching Filtration to Health Requirements, Phase II, American Society of Heating, Refrigerating and Air Conditioning Engineers, 1991-1993(with D. Pui, D. Vesley and A. Streifel).

Investigate and Identify Means of Controlling Virus in Indoor Air by Ventilation, Filtration or Source Removal, American Society of Heating, Refrigerating and Air Conditioning Engineers, 1993(with L. Brosseau, D. Vesley and S. Goyal).

Modeling the Cleaning Process in Megasonic Cleaning Tanks, Sandia National Laboratories, 1994-1998(with D. B. Kittelson)

Commercial Building HVAC Requirements for Maintaining Good Indoor Air Quality, U. S. EPA, Air and Energy Engineering Research Laboratory, RTP, 1994-1998(with J. W. Ramsey, K. Janni)

Identification of Contaminants, Exposures, Effects and Control Options for Construction/Renovation Activities, American Society of Heating, Refrigerating and Air Conditioning Engineers, 1994-1995(with D. Grimsrud, K. Janni and A. Streifel)

Identification and Characterization of Effluents from Various Cooking Appliances and Processes as Related to Optimum Design of Kitchen Ventilation Systems, American Society of Heating, Refrigerating and Air Conditioning Engineers, 1995-1998(with D. Y. H. Pui and J. W. Ramsey)

Evaluation of Biofiltration of Air, An Innovative Air Pollution Control Technology, American Society of Heating, Refrigerating and Air Conditioning Engineers, 1995-1997(with K. Janni, W. Maier, B. Bridges and D. Vesley)

Testing CLEAR^{TM} Device, United Technologies Research Center, 1995-1997(with D. Vesley)

Identification and Effectiveness of Current Methods Applied and Criteria Applied in Non-Routine Cleaning and Decontaminating of Air Ducts and Other HVAC Components, American Society of Heating, Refrigerating and Air Conditioning Engineers, 1996-1998(with L. Brosseau and D. Vesley)

Development of Snow Melting Load Design Algorithms and Data for Locations Around the World, American Society of Heating, Refrigerating and Air Conditioning Engineers, 1996-1999(with J. Ramsey)

Modeling Particle Deposition Tool, Submicron Systems, Inc., 1996-1997.

Effects of Air velocity on Grease Deposition in Exhaust Ductwork, American Society of Heating, Refrigerating and Air Conditioning Engineers, 1998-2000(with D. Y. H. Pui and J. W. Ramsey)

Testing of Grease Particulate Removal Efficiency of Various Commercial Kitchen Hood Grease Baffles, Extractors and Filters, Greenheck, 1999-2000.

Development of a Draft Method of Test for Determining Grease Removal Efficiencies, American Society of Heating, Refrigerating and Air Conditioning Engineers with subcontract through University of California, Riverside, 2000-2001.

Experimental Characterization of Phillips Packed Bed Media as a Filter Using Liquid Challenge Aerosol, Phillips Plastics Corporation, 2002.

Experimental Characterization of New Air Purifier Using Microbial Challenge Aerosol, Donaldson Corporation, 2003.

Development of a Standard Method of Test for Commercial Kitchen Effluent Grease Removal Devices: Phases 1&2, Fisher-Nickel, Inc., 2003-2004.

Integrated Building Systems for Energy Efficiency and Renewable Technologies, IREE Seed Grant, 2004. (with J. Carmody)

Integrated Biological Data from Filter Samples in Buildings, U.S. Department of Homeland Security, 2004-2006. (with P. Raynor and S. Goyal)

Threat Agent Cloud Tactical Intercept, Los Alamos National Laboratory (DARPA), 2005.

Characterization of Effluents from Additional Cooking Appliances, ASHRAE, 2006-2007(with J. Ramsey).

Experimental and Numerical Simulation of the Fate of Airborne Nanoparticles from a Leak in a Manufacturing Process to Assess Worker Exposure, NSF, 2006-2010 (with D. Y. H. Pui and H. Fissan)

Method of Test to Evaluate Field Performance of Commercial Kitchen Ventilation Systems, ASHRAE, 2007-2009.

Characterize the Particulate and Vapor Chemical Emissions from an Underfired Broiler Cooking Hamburger, Bay Area Air Quality Management District, 2007-2008.

Characterize Particulate and Vapor Grease Emissions from a new Hamburger Cooking Appliance with and Without a Catalyst, Burger King, Inc., 2008.

Grease Deposition Sensor Development, Halton Group Americas, 2008.

Development of a Calibration Reference Device for use with Test Standard ANSI/ASHRAE 52.2-2007, ASHRAE, 2008-2011 (with V. Marple).

Measurement of Particle Sizes Associated with Airborne Viruses, NIOSH, 2008-2013 (with S. Goyal and P. Raynor).

Combining Geothermal Energy Production and CO2 Sequestration for Carbon-Negative Electricity Generation, IREE, 2009-2012 (with M. Saar).

A Novel Method Using CO2 and Geothermal Resources for Sustainable Energy Production and Storage, NSF, 2012-2016 (with M. Saar, S. J. Taff, J. B. Randolph and J. M. Bielicki)

Airborne Virus Particle Sampling, Boeing Commercial Aircraft, 2013-2014 (with D. Y. H. Pui).

Refereed Journal Publications

Kuehn, T.H. and Goldstein, R.J., "An Experimental and Theoretical Study of Natural Convection in the Annulus Between Horizontal Concentric Cylinders," J. Fluid Mech., Vol. 74, pp. 695-719 (1976).

Kuehn, T.H. and Goldstein, R.J., "Correlating Equations for Natural Convection Heat Transfer Between Horizontal Circular Cylinders," Int. J. Heat Mass Transfer, Vol. 19, pp. 1127-1134 (1976).

Kuehn, T.H., "Radial Heat Transfer and Critical Biot Number with Radiation, Uniform Surface Heat Generation, and Curvature Effects in Convection," J. Heat Transfer ASME, Vol 100, pp. 374-376 (1978).

Kuehn, T.H. and Goldstein, R.J., "An Experimental Study of Natural Convection Heat Transfer in Concentric and Eccentric Horizontal Cylindrical Annuli," J. Heat Transfer ASME, Vol. 100, 635-640 (1978).

Shapiro, H.N. and Kuehn, T.H., "Second Law Analysis of the Ames Solid Waste Recovery System," Energy, Vol. 5, pp. 985-991 (1980).

Kuehn, T.H. and Goldstein, R.J., "Numerical Solution to the Navier-Stokes Equations for Laminar Natural Convection About a Horizontal Circular Cylinder," Int. J. Heat Mass Transfer, Vol 23, pp. 971-979 (1980).

Kuehn, T.H. and Goldstein, R.J., "A Parametric Study of Prandtl Number and Diameter Ratio Effects on Natural Convection Heat Transfer in Horizontal Cylindrical Annuli," J. Heat Transfer ASME, Vol. 102, pp. 768-770 (1980).

Szydlowski, R.F. and Kuehn, T.H., "Analysis of Transient Heat Loss in Earth Sheltered Structures," American Underground Space J., Vol 5, pp. 237-246 (1981).

Kuehn, T.H., "Field Heat-Transfer Measurements and Life-Cycle Cost Analysis of Four Wood-Frame Wall Construction," ASHRAE Transactions, Vol 88, Pt. 1, pp. 651-665 (1982).

Kwon, S.S., Kuehn, T.H., and Lee, T.S., "Natural Convection in the Annulus Between Horizontal Circular Cylinders with Three Axial Spacers," J. Heat Transfer ASME, Vol. 104, pp. 118-124 (1982).

Kuehn, T.H., "Temperature and Heat Flow Measurements from an Insulated Concrete Bermed Wall and Adjacent Floor," J. Solar Energy Engineering ASME, Vol. 104, pp. 15-22 (1982).

Kuehn, T.H., Kwon, S.S., and Tolpadi, A.K., "Similarity Solution for Conjugate Natural Convection Heat Transfer From a Long Vertical Plate Fin," Int. J. Heat Mass Transfer, Vol 26, pp. 1718-1721 (1983).

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Courses Taught-University of Minnesota

Quarter

- ME 3020 Mechanical Engineering Computation
- ME 3301 Thermodynamics
- ME 3303 Applied Thermodynamics
- ME 5254 Design Morphology with Applications
- ME 5342 Heat Transfer
- ME 5603 Thermal Environmental Engineering
- ME 5604 Heating and Cooling Loads in Buildings
- ME 5605 Refrigeration and Air Conditioning Systems
- ME 5630 Thermal Environmental Engineering Senior Laboratory
- ME 8800 Modern Developments in Mechanical Engineering

Semester

- ME 4054W Design Projects-course coordinator or project advisor
- ME 4131W Thermal Environmental Engineering Laboratory
- ME 5090 Advanced Engineering Problems
- ME 5101 Vapor Cycle Systems
- ME 5103 Thermal Environmental Engineering
- ME 5105 HVAC System Design

Graduate Student Advising

Iowa State University

Larry Scheier	MS, 1979
Thesis Title:	Theoretical and Experimental Performance of a Compound Parabolic Concentrator for Several Absorber Configurations
Jeffrey Balvanz	MS, 1980
Thesis Title:	Experimental and Theoretical Investigation of Laminar Flow and Heat Transfer in Rectangular Ducts with One Heated Porous Wall

Richard Szydlowski	MS, 1980
Thesis Title:	Analysis of Transient Heat Loss in Earth Sheltered Structures
Kam Leong	MS, 1981
Thesis Title:	An Analysis of the Iowa State University Energy Research House Solar Domestic Hot Water Preheating System
Anil Tolpadi	MS, 1983
Thesis Title:	Experimental Numerical Study of Conjugate Natural Convection Heat Transfer from Fins

University of Minnesota

Sadek Youssef	MS, 1986
Paper Title:	Simulation Study of a Point-Focus Porous or Honeycomb Matrix Absorber Solar Receiver
Eric Grald	MS, 1986
Thesis Title:	An Analytical Study of Natural Convection Heat Transfer in Annular Sectors
Chuen-Jinn Tsai	MS, 1986 (with D. Pui)
Thesis Title:	Fundamental Study of Purge Air System
Ilango Shanmugavelu	MS, 1987
Thesis Title:	Numerical Modeling of Fluid Flow and Ventilation Effectiveness in a Room
Anil Tolpadi	PhD, 1987
Thesis Title:	Coupled Three-Dimensional Conduction and Natural Convection Heat Transfer
Hwataik Han	PhD, 1988
Thesis Title:	Double Diffusive Natural Convection in a Vertical Rectangular Enclosure
Brian Edwards	MS, 1989 (with P. Blackshear)
Thesis Title:	Extracorporeal Autoperfused Multiple Organ Block Preservation for Transplantation
Scott Forbes	PhD, 1989
Thesis Title:	In-Line Particle Holography Applied to Fluid Velocity Measurement
Richard O'Brien	MS, 1990
Paper Title:	A Computer Simulation of the Linde Air Liquefaction Cycle
Jun Zhao	PhD, 1990 (with B.Y.H. Liu)
Thesis Title:	Thermodynamics and Particle Formation During Vacuum Pump-Down
Hongmei Liang	MS, 1990
Paper Title:	Irreversibility Analysis of a Water to Water Vapor Compression Heat Pump
James Gratzek	MS, 1990(with D. Y. H. Pui)
Paper Title:	Comparison of Numerical and Experimental Studies of Clean Room and Particle Transport
James Douglas	MS, 1991

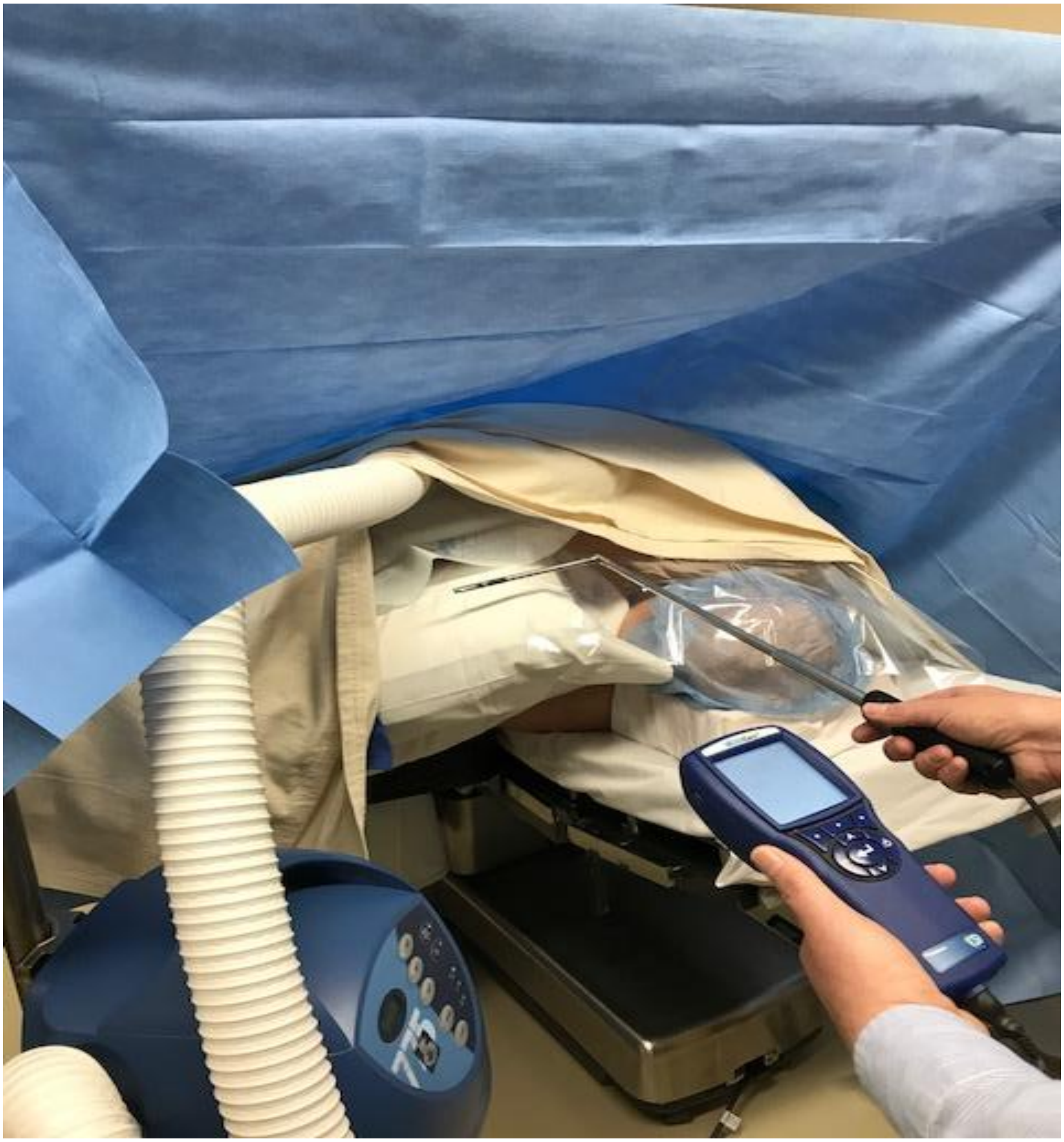
Thesis Title:	Determination of Moisture Transport Properties for Common Building Materials: Methods and Measurements
Cindy Berg Paper Title:	MS, 1991 Matching Filtration to Health Requirements
Karim Elayed Thesis Title:	MS, 1992 Implementation of a Robust Semi-Direct Finite-Difference Method to Strongly Coupled Turbulent Flow Differential Equations
Mark Corpron Thesis Title:	MS, 1992 (with J. Ramsey) Design and Characterization of a Ventilation Chamber
Yi Wu Paper Title:	MS, 1992 (with B. Y. H. Liu) Particle Contamination below a Robot Arm in a Clean Room
Mark Perkovich Thesis Title:	MS, 1992 (with J. Ramsey) Experimental Study of a Reciprocating Refrigeration Compressor
Jianqing Xu Thesis Title:	MS, 1993 Numerical Studies of Ventilation in Rooms with Ceiling Air Supply
Scott D. Dahl Thesis Title:	MS, 1993 Determination of the Moisture Storage and Transport Properties of Common Building Materials
Barbara Gacek Paper Title:	MS, 1994 The Deposition Distribution of Grease Sized Particles in Two Residential Kitchen Range Exhaust Hoods
Hongmei Liang Thesis Title:	PhD, 1994 Room Air Movement and Contaminant Transport
John W. Marshall Thesis Title:	MS, 1994 Ventilation Efficiency in a Scale Model Bone Marrow Transplant Room
Zhiqin Chen Thesis Title:	MS, 1995 Experimental Studies of Thermal Conditions in a Room Governed by Natural Convection
Michael Doerr Thesis Title:	MS, 1996 Ventilation Efficiency and the Effects of Thermal Buoyancy and Room Air Change Rate in a One-Half Scale Model Hospital Isolation Room
Yi Wu Thesis Title	PhD, 1997 (with B. Y. H. Liu) Modeling and Simulation of Megasonic Cleaning Tanks
Hee Siew Han Thesis Title	MS, 1997 Efficacy of Antimicrobial Treatments on Loaded Filters
Li-Ming Lo Thesis Title:	MS, 1997 Numerical Studies of Airflow Movement and Contaminant Transport in Hospital Operating Rooms
Scott Ward Paper Title:	MS, 2000 Operation Efficiency Study, Schwan's Super Rink, Blaine, MN

Jitesh Vidhani Paper Title:	MS, 2000 A Study of Multi-Link Models of Human Postural Dynamics and Control
William Gerstler Thesis Title	PhD, 2000 Turbulent Aerosol Deposition in Large and Small Square Flow Passages
Handi Tjandra Paper Title	MS, 2001 Grease Vapor Deposition in Kitchen Exhaust Ductwork
Ching Hsu Yang Thesis Title	PhD, 2001 Total and Spatial Particle Removal from Silicon Wafers by Megasonic Cleaning
Humberto Ortiz Paper Title	MS, 2001 Velocity and Turbulence Intensity Measurements in a Square Duct
Choongkee Seong Thesis Title	MS, 2002 Development of a Test Apparatus for Determining Efficiency of Filter Media on Bioaerosols
Mark Geronime Paper Title	MS, 2002 The Fatal Link Between Aspergillosis and Construction/Renovation in Health Care Facilities
Tanya Santers Paper Title	MS, 2003 The Development and Implementation of Nanostructured Alumina-Titania Coatings
Charles Bartlett Paper Title	MS, 2005 Analysis of Residential Dehumidification Methods: Energy Usage and Costs
James Farnsworth Thesis Title:	MS, 2005 An Evaluation of Ventilation Filters in Building Air-Handling Units as Collection Media for High Volume Microorganism Sampling Applications
Nicholas Stanley Thesis Title:	MS, 2007 Background Airborne Bacteria and Virus Populations in and near Buildings Using Ventilation Filters as Long-Term Bioaerosol Collection Devices
Jesse Ahlert Paper Title:	MS, 2008 New Residential Construction: A Guide to Building a Sustainable Home in Minnesota
Mike Biorn Paper Title:	MS, 2008 Design of Test Kitchen Air Handling System for ASHRAE 1376-RP
Brian Ng Paper Title:	MS 2008 Feasibility Study of Cogeneration in an Ethanol Production Plant
Weihua Tang	Ph.D., 2008 Effects of Temperature, Relative Humidity, and Air Flow on Microbial Growth on Loaded Ventilation Filters
Nikhil Ramesh	MS, 2010

Thesis Title:	Grease Particle Deposition Measurements in a Kitchen Exhaust Duct for the Development of Low Cost Grease Sensors
Nicholas Stanley Thesis Title:	Ph.D., 2010 The Fate of Airborne Nanoparticles Released from a Leak in a Nanoparticle Production Process into a Simulated Workplace Environment
Brian Janke Thesis Title:	MS, 2011 Investigation of Geothermal Power Plant Performance using Sequestered Carbon Dioxide as a Heat Transfer or Working Fluid
Meng Zhang Thesis Tile:	Ph.D., 2012 Aerosol Particle Scavenging by Large Droplets
Brian Jennissen	MS, 2013 (coursework option)
Andrew Mevissen	MS, 2013 (coursework option)
Charles Sawyer Paper Title:	MS, 2013 Determining the Water Content of a CO2 Plume Geothermal Production Well Using CO2-H2O Solubility Models
Song Ge Thesis Title:	Ph.D., 2014 Viral Aerosol Survivability, Transmission, and Sampling in an Environmental Chamber
Zhili Zuo Thesis Title:	Ph.D., 2014 Measurement and Filtration of Virus Aerosols
Benjamin Adams Thesis Title:	Ph.D., 2015 On the Power Performance and Integration of Carbon-dioxide Plume Geothermal (CPG) Electrical Energy Production
Margaret Peterson Thesis Title:	MS, 2015 An Investigation into the Seasonal Economic and Energy Performance of CO_2 Plume Geothermal (CPG) Power Plants.

3M Lab Measurements

Head: 3" from blanket edge (L)



BH Status		Temperature	Airflow
Off		66.2 ºF	5 ft/min
On (high fan speed, ambient)		66.9 ºF	120 ft/min
On (high fan speed, 43 ºC)	1 min	66.4 ºF	90 ft/min
	2 min	67.9 ºF	93 ft/min
	3 min	69.3 ºF	102 ft/min
	4 min	70.9 ºF	104 ft/min
	5 min	72.8 ºF	107 ft/min

	6 min	73.8 ºF	112 ft/min
	7 min	74.0 ºF	105 ft/min
	8 min	74.5 ºF	110 ft/min
	9 min	74.7 ºF	108 ft/min
	~15 min	74.9 ºF	95 ft/min
	~16 min	74.9 ºF	90 ft/min

Head: 6" from blanket edge (R)

Off	66.4 ºF	0—1 ft/min

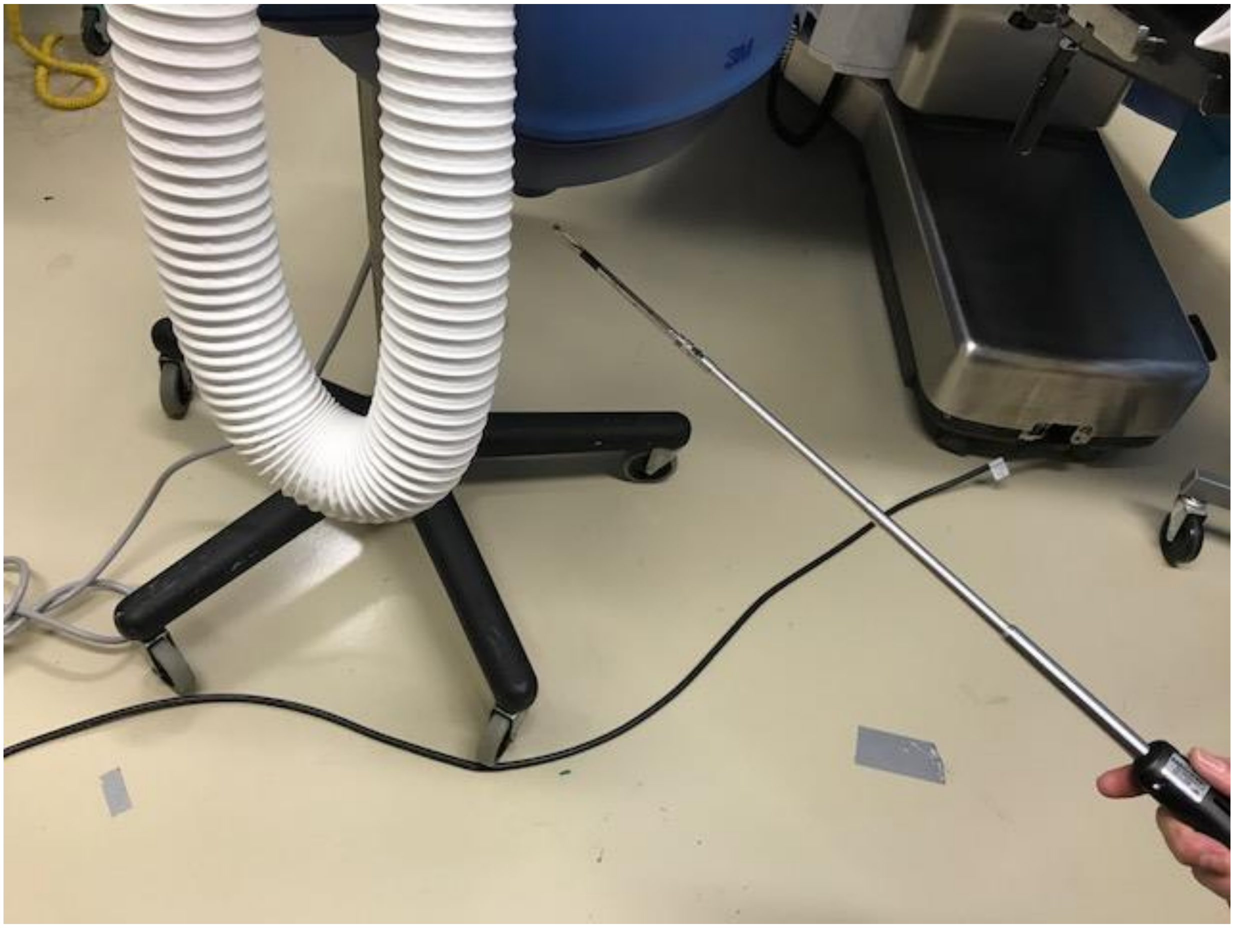
Inside edge of drape (R)

Off	67.3 ºF	2 ft/min
On (high fan speed, ambient)	66.7 ºF	3 ft/min
On (high fan speed, 43 ºC)	72.1 ºF	4 ft/min

Inside edge of drape (L)

Off	67.5 ºF	4 ft/min
On (high fan speed, ambient)	66.7 ºF	8 ft/min
On (high fan speed, 43 ºC)	72.4 ºF	6 ft/min

Directly under BH filter (2" below intake, Center) (photo shows probe further away)

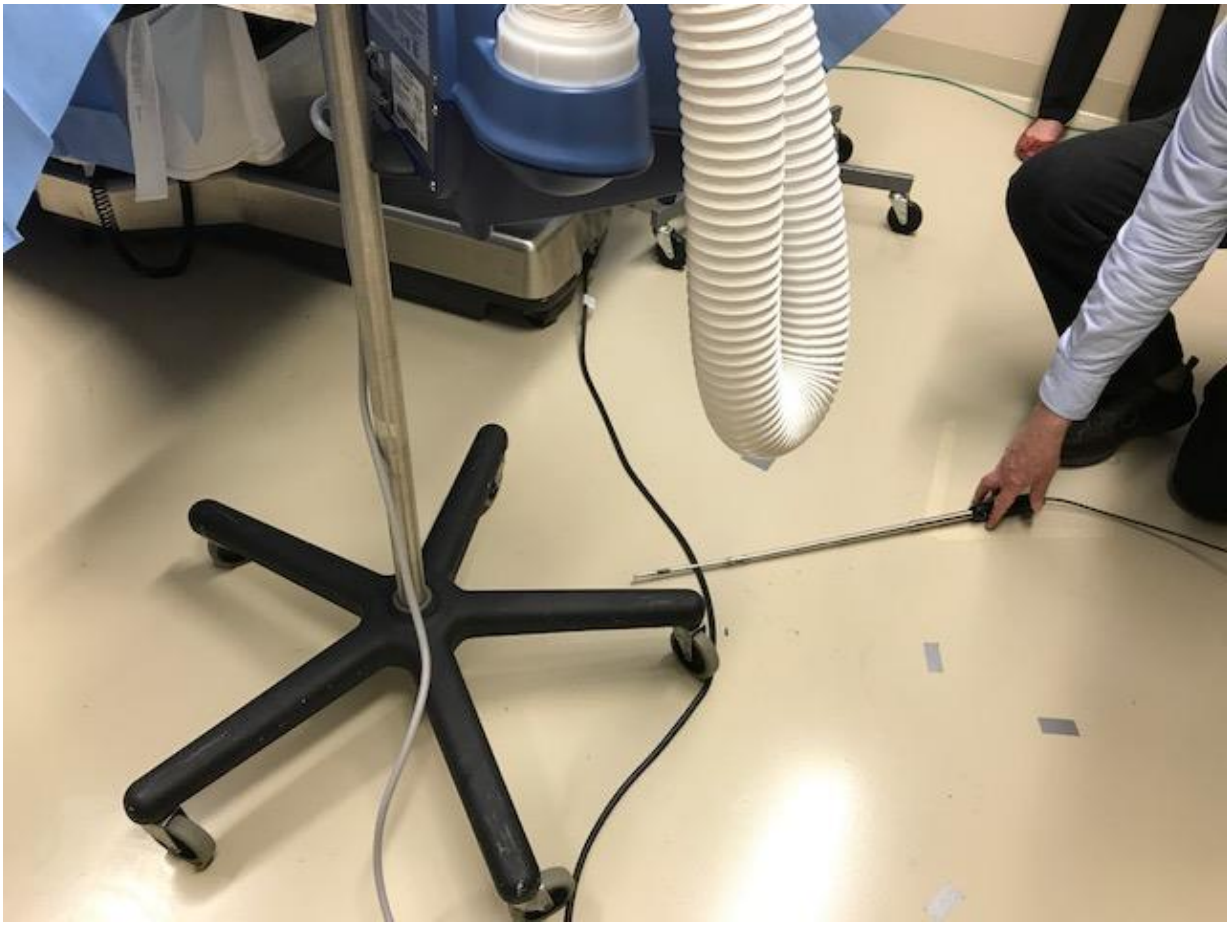


Off	68.0 ºF	2 ft/min
On (high fan speed, ambient)	65.9 ºF	220 ft/min
On (high fan speed, 43 ºC)	67.7 ºF	220 ft/min

1 ft. under BH (Center)

Off	68.2 ºF	5 ft/min
On (high fan speed, ambient)	65.6 ºF	12 ft/min
On (high fan speed, 43 ºC)	67.8 ºF	5 ft/min

Floor under BH (Center)



Off—Parallel	68.4 ºF	0 ft/min
Off—Perpendicular	68.2 ºF	2 ft/min
On—Parallel	65.2 ºF	20 ft/min
On—Perpendicular	65.1 ºF	3 ft/min
On (43ºC—Parallel)	67.7 ºF	20 ft/min
On (43ºC—Perpendicular)	67.7 ºF	5 ft/min

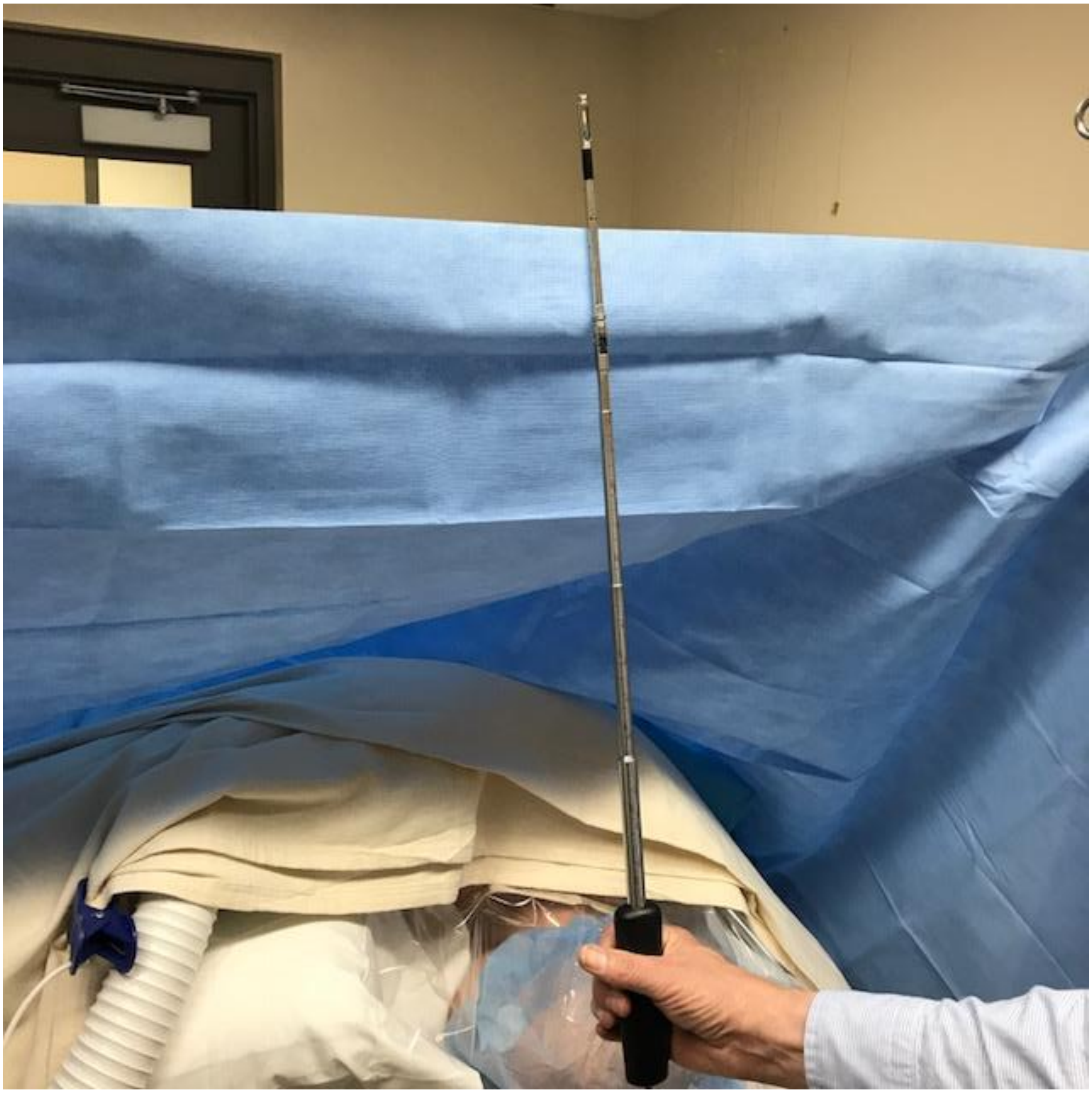
6" below BH

On (high fan speed, 43 ºC)	67.6 ºF	50 ft/min

Top of anesthesia screen, 3” below top (Center)

Off	69.3 ºF	1 ft/min
On (high fan speed, ambient)	66.7	27 ft/min

Over center of anesthesia screen, 3" above top (Center)



On (high fan speed, ambient)	64.9 ºF	3 ft/min

Head-height outside of anesthesia screen (R)

Off	69.1 ºF	1 ft/min

Head-height outside of anesthesia screen (L)

Off	70.2 ºF	0 ft/min

3" Over Hip

Off—parallel		70.7 ºF	15 ft/min
Off—Perpendicular		71.4 ºF	30 ft/min
On—parallel		64.9 ºF	20 ft/min
On~~ff~~—Perpendicular		64.6 ºF	12 ft/min
On (high fan speed, 43 ºC)	1 min—parallel	70.2 ºF	10 ft/min
	2 min—parallel	69.8 ºF	9 ft/min
	3 min—parallel	68.3 ºF	13 ft/min
	4 min—parallel	68.0 ºF	5 ft/min
	Perpendicular	67.8 ºF	10 ft/min

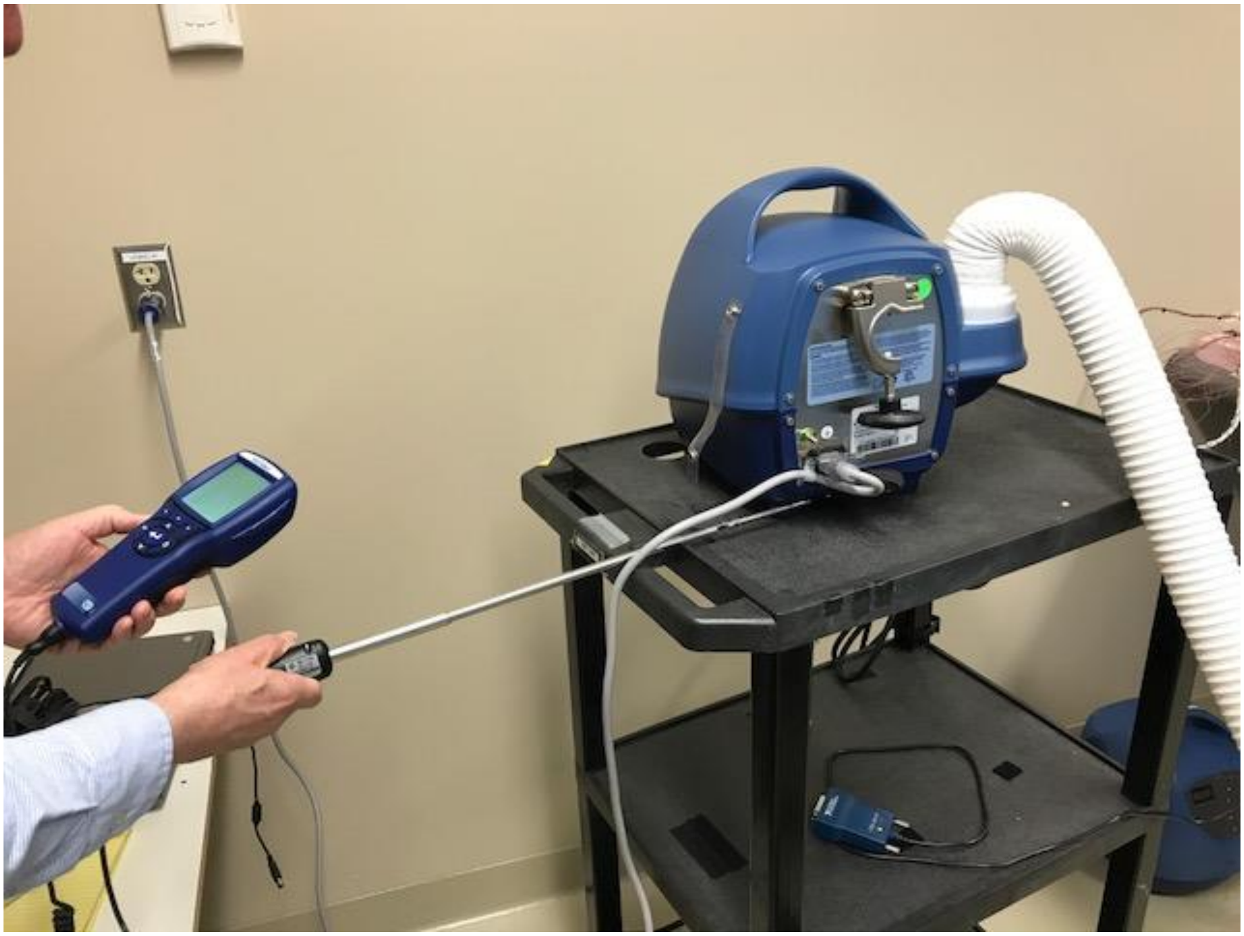
Under linear slot diffuser air supply on ceiling (Front) – ½ inch from supply

Right (18" from wall)	72.3 ºF	670 ft/min
Center	72.2 ºF	330 ft/min
Left (18" from wall)	71.8 ºF	1550 ft/min

Under linear slot air return on ceiling (Back) – ½ inch from intake

Right	69.6 ºF	270 ft/min
Center	69.3 ºF	310 ft/min
Left	69.8 ºF	680 ft/min

BH on Cart – four sides of unit between bottom of unit and top of cart



Center of back	67.4 ºF	340 ft/min
Bottom side of BH (opposite side of hose)	67.1 ºF	440 ft/min
Bottom side of BH (side of hose)	67.7 ºF	450 ft/min
Probe under front	67.7 ºF	200 ft/min

CERTIFICATE OF CALIBRATION AND TESTING

TSI Incorporated, 500 Cardigan Road, Shoreview, MN 55126 USA
Tel: 1-800-874-2811 1-651-490-2811 Fax: 1-651-490-3824 http://www.tsi.com

ENVIRONMENT CONDITIONS		
TEMPERATURE	75.7 (24.3)	°F (°C)
RELATIVE HUMIDITY	23	%RH
BAROMETRIC PRESSURE	29.06 (984.1)	inHg (hPa)

MODEL	966
SERIAL NUMBER	P15380015

☒ AS LEFT ☒ IN TOLERANCE
☐ AS FOUND ☐ OUT OF TOLERANCE

– CALIBRATION VERIFICATION RESULTS –

TEMPERATURE VERIFICATION SYSTEM T-101 *Unit: °F (°C)*

#	STANDARD	MEASURED	ALLOWABLE RANGE	#	STANDARD	MEASURED	ALLOWABLE RANGE
1	32.0 (0.0)	31.8 (−0.1)	31.5~32.5 (−0.3~0.3)	2	140.0 (60.0)	139.8 (59.9)	139.5~140.5 (59.7~60.3)

HUMIDITY VERIFICATION SYSTEM H-102 *Unit: %RH*

#	STANDARD	MEASURED	ALLOWABLE RANGE	#	STANDARD	MEASURED	ALLOWABLE RANGE
1	10.0	9.3	7.0~13.0	4	70.0	67.4	67.0~73.0
2	30.0	28.2	27.0~33.0	5	90.0	87.2	87.0~93.0
3	50.0	47.9	47.0~53.0				

VELOCITY VERIFICATION SYSTEM V-107 *Unit: ft/min (m/s)*

#	STANDARD	MEASURED	ALLOWABLE RANGE	#	STANDARD	MEASURED	ALLOWABLE RANGE
1	0 (0.00)	1 (0.01)	−3~3 (−0.02~0.02)	7	657 (3.34)	650 (3.30)	637~676 (3.24~3.44)
2	35 (0.18)	36 (0.18)	32~38 (0.16~0.19)	8	1000 (5.08)	1005 (5.11)	970~1030 (4.93~5.23)
3	65 (0.33)	65 (0.33)	62~68 (0.32~0.35)	9	1484 (7.54)	1481 (7.52)	1440~1529 (7.31~7.77)
4	100 (0.51)	100 (0.51)	97~103 (0.49~0.53)	10	2505 (12.72)	2509 (12.75)	2430~2580 (12.34~13.11)
5	161 (0.82)	161 (0.82)	156~165 (0.79~0.84)	11	4529 (23.01)	4532 (23.02)	4393~4665 (22.32~23.70)
6	331 (1.68)	330 (1.67)	321~341 (1.63~1.73)	12	8007 (40.67)	8003 (40.65)	7766~8247 (39.45~41.89)

TSI does hereby certify that the above described instrument conforms to the original manufacturer's specification (not applicable to As Found data) and has been calibrated using standards whose accuracies are traceable to the United States National Institute of Standards and Technology (NIST) or has been verified with respect to instrumentation whose accuracy is traceable to NIST, or is derived from accepted values of physical constants. TSI's calibration system is registered to ISO-9001:2015.

Measurement Variable	System ID	Last Cal.	Cal. Due
DC Voltage	E001653	10-21-16	04-30-18
Pressure	E001718	04-21-17	10-31-17
Velocity	E004603	09-19-12	09-19-17
Temperature	E003987	03-15-17	09-30-17
Temperature	E001643	04-24-17	10-31-17
Pressure	E002389	02-08-17	08-31-17
Temperature	E003986	03-15-17	09-30-17
Humidity	E003539	08-11-16	08-11-17

[signature]
CALIBRATED

May 8, 2017
DATE

Doc ID: CERT_GEN_WCC

TSI P/N 2300157

Exhibit C:

Calculation of potential particle removal between the bottom of a Bair Hugger and the floor which would also be the case when the Bair Hugger is sitting on a cart with a flat top

Both models of Bair Hugger, 505 and 750/775, are considered. The highest velocity below a Bair Hugger will be near the entrance to the filter between the bottom of the unit and the floor as this has the minimum cross sectional area and the total air flow rate entering the filter passes through this region.

Model 505:

The filter opening on the bottom of the Bair Hugger is circular with an outer diameter of 6.125 in. The minimum distance between the bottom of the unit and the surface it rests on is approximately 5/8 in. The cross sectional area formed by this cylindrical passage is

$A = \pi DH$ or $\pi \times 6.125$ in x 0.626 in = 12.03 in^2 or 0.0835 ft^2.

The air flow rate provided by this model is 27 cfm (cubic ft per minute) so the mean air velocity through the area above becomes

$V = 27$ ft^3/min /(0.0835 ft^2) = 323 ft/min or 5.39 ft/sec or 1.64 m/sec.

This is the maximum mean air velocity below the Bair Hugger.

One method to estimate the likelihood of particle removal from a surface is to consider Figure 6.4 from the text Aerosol Technology Properties, Behavior, and Measurement of Airborne Particles by William C. Hinds. This figure is provided below. The results were obtained by measuring the removal of round glass spheres from a smooth surface by blowing air. Bacteria and the particles they are attached to are typically not as smooth and round as these glass beads and would be more difficult to remove. The smallest beads shown in the figure are 15.9 microns, larger and easier to remove than bacteria containing particles. Considering the curve for 15.9 micron sized glass beads, at a velocity of 1.64 m/sec calculated above, the figure indicates that the fraction removed would be very close to zero. The results show that any velocity less than about 30 m/sec would have very little effect on 15.9 micron sized round glass particles. In summary, the results from this figure indicate that bacteria-containing particles less than 15.9 microns in size attached to the floor would not be removed by the maximum velocity provided by a Bair Hugger Model 505.

A more quantitative approach can also be taken by using more recent particle attachment force/removal theory. The air velocity gradient near a flat surface will allow the drag force on a particle sitting on the surface to be estimated. Then this force is compared to the attachment forces to determine whether the particle will move. The results of this approach are given below.

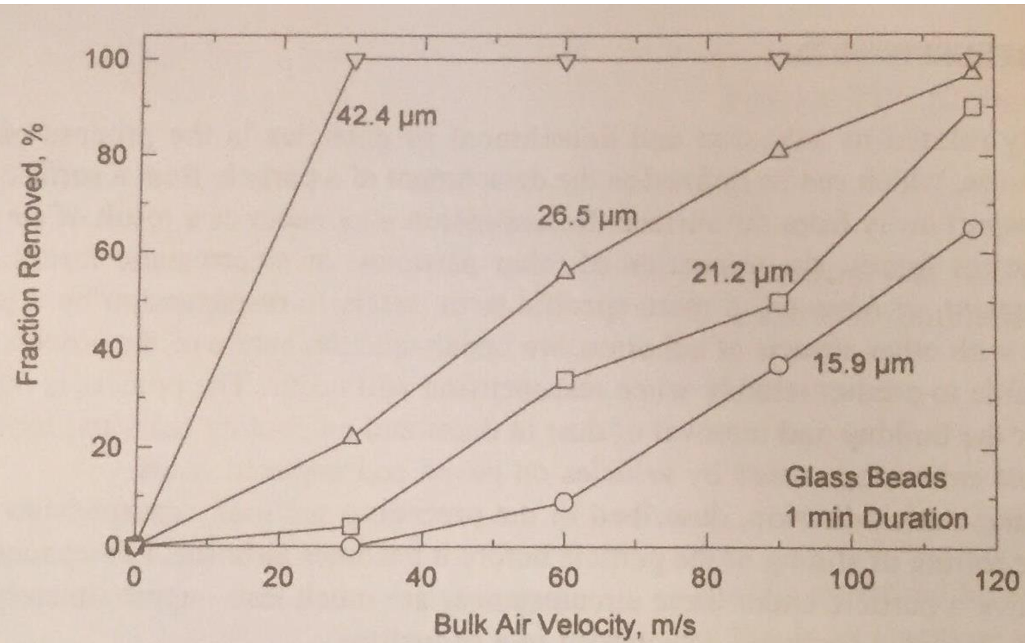


FIGURE 6.4 Particle reentrainment versus bulk air velocity for four particle sizes. Data from Corn and Stein (1965).

The air velocity gradient near the surface is determined first. This is a function of the flow regime determined by the Reynolds number. The flow is essentially between two parallel plates (the bottom of the Bair Hugger and the floor). The hydraulic diameter of flow between two parallel plates is equal to twice the plate spacing or 2 x 5/8 in. in this case. Using air density and dynamic viscosity at a temperature of 70 F and standard sea level pressure the Reynolds number becomes:

$Re_{Dh} = 2 \times \rho \times V \times D/\mu$

$= 2 \times 0.07493\ lbm/ft^3 \times 323\ ft/min \times 0.625\ in./(0.044\ lbm/ft\ hr) \times (1\ ft/12\ in.) \times (60\ min/hr)$

$= 3.44 \times 10^3$

This indicates that the flow is in the transition regime between laminar and turbulent flow so both will be considered to determine which has the higher velocity shear rate near the floor and the most likely to remove attached particles.

For laminar flow, the velocity gradient at the floor is determined by

$dv/dy = 3 \times V/h$

where V is the mean velocity and h is one-half the distance between the two surfaces,

$dv/dy = 3 \times [(5.39\ ft/sec)/(0.625\ in/2)] \times (12\ in/ft) = 621/sec$

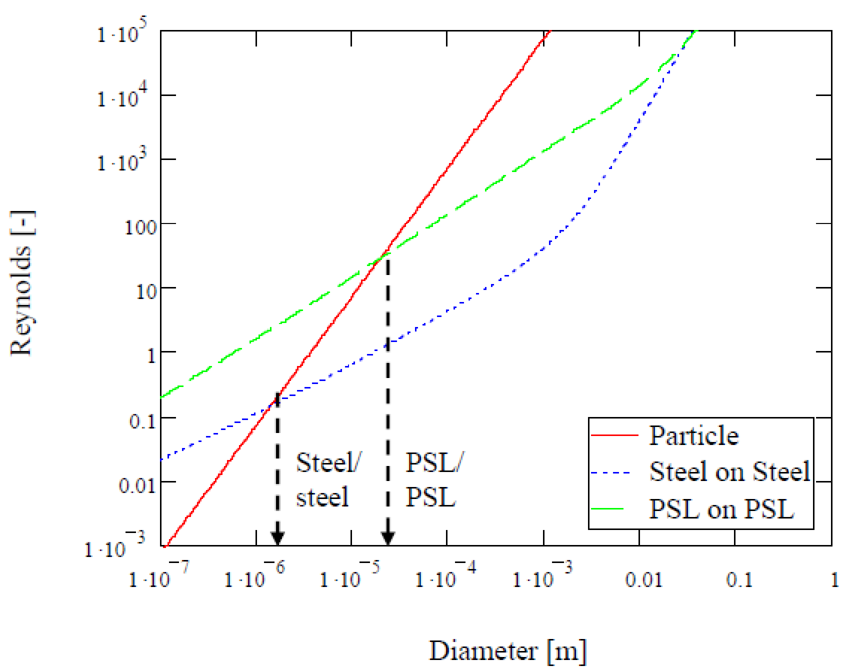
Any length dimension can be used with this such as 621 ft/sec/ft or 621 micron/sec/micron. The velocity gradient for turbulent flow was also determined (94/sec) which is less than the laminar value (621/sec) so the laminar value is used in subsequent calculations. This ratio is counterintuitive but can occur in the transition regime as discussed by White.

The drag force on a particle attached to a surface is determined using the velocity at the particle mid-height so for a 10 micron particle the velocity is computed at a distance of 5 microns from the surface.

$V_{5\mu m}$ = 5 μm x 621 μm/sec/μm = 3105 μm/sec = 3.11 x 10^{-3} m/sec = 0.0102 ft/sec = 0.12 in/sec

The Reynolds number for this velocity acting on a 10 micron particle becomes 2.1 x 10^{-3}.

The figure below was provided by Zoeteweij et al. who considered the threshold for spherical particle removal from surfaces by fluid drag forces. The figure shows the particle Reynolds number on the vertical axis and the particle diameter in microns on the horizontal axis. The red line can be interpreted as the particle drag force or removal force, the blue curve the adhesion force for spherical steel particles on a steel surface and the green curve as polystyrene latex (PSL) spherical particles on a PSL surface. When the red line is higher than one of the other curves, the particles can be moved by rotation or rolling, the first step in removal. When the red line is below, the particles do not move and remain attached to the surface. In the present case, the Reynolds number for 10 micron-sized particles was calculated to be 2.1 x 10^{-3}. For particles of this size, the Reynolds number would have to be approximately 0.1 before spherical steel



particles would begin to rotate and approximately 1.0 before PSL particles would be moved. As bacteria particles themselves and those attached to other particles are not spheres and are more difficult to move on a surface than the steel and PSL spheres shown here, the curve indicating their initial movement would be higher on the graph than the green line for the PSL spheres. In summary, the velocity below a Bair Hugger model 505 and the floor it is resting on is much less than what would be required to remove 10 micron-sized particles from the floor.
The air velocity would have to be increased by a factor of at least 5000.

Model 750:

Similar calculations have been made for the Model 750 unit. The maximum velocity between the unit and the floor was determined to be approximately 8.6 ft/sec or 516 ft/min. Although the maximum velocity measured between the bottom of a model 750 Bair Hugger and the top of a cart was 450 ft/min as shown in Exhibit B, the value of 516 will be used here as a conservative value. This results in a Reynolds number of 5.9×10^3. As this is in the turbulent flow regime, the turbulent friction factor was used to estimate the velocity gradient at the floor which was found to be 200/sec. The Reynolds number for a 10 micron-sized particle becomes
6.7×10^{-4} which is below the horizontal axis of the figure shown above from Zoeteweij et al.

In summary, the Bair Hugger Model 750 and its very similar unit, Model 775, are not capable of removing spherical particles of 10 microns or less from the floor. Bacteria would be more difficult to remove because they are not perfect spheres and have increased contact area between them and the surface. This results in higher adhesion forces than for spherical particles. They are also less likely to begin to rotate at the same air velocity as spherical particles; that also increases the velocity necessary to remove them. An air velocity of at least 5000 times larger than provided by a Bair Hugger would be required to remove bacteria particles from the floor.

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Exhibit D

Calculation of the Effect of Thermal Buoyancy on the Motion of Warm Air Leaving the Bair Hugger Blanket:

The measurements in Exhibit B show that the temperature of the air leaving the bottom of the blanket at both sides is approximately 72 F when a Bair Hugger Model 750 is turned on and set at 43 C (109 F) and the background air in the room is approximately 66 F. This is approximately the design temperature of the air that leaves an OR through the return grilles located near the floor (68 to 74 F, Reference 1). No significant thermal buoyancy is expected as the surrounding air temperature should be very similar.

Velocity and temperature measurements made near the rear of the blanket showed an air temperature of approximately 75 F and an air velocity of approximately 110 ft/min. The effect of thermal buoyancy on an air jet such as this can be estimated by determining the Archimedes number, Ar. This is a dimensionless ratio of the buoyant force divided by the momentum force often given the ratio Gr/Re^2 where Gr represents the Grashof number for thermal buoyancy and Re represents the Reynolds number for forced flow. Reference 2 indicates that when Ar is nearly equal to 1, the buoyant and forced flow effects are nearly equal. When the value is much less than 1.0, buoyancy is not important and the forced flow dominates. The 2013 ASHRAE Handbook of Fundamentals, Ch 20 (reference 3) shows that Ar can be written as:

$Ar = g\ L\ \Delta T/(T_{amb}\ V^2)$

Where

g = acceleration of gravity

L = a length scale, in this case the width of the jet

Δt = temperature difference between the jet and ambient

T_{amb} = the mean absolute temperature of the jet and its surroundings

V = the jet velocity

Inserting measured values using a length of 1 inch for the width of the jet that was measured near the edge of the blanket:

$Ar = (32.2\ ft/sec^2)\ (1\ in.)\ (75 - 66\ F)/((460 + 70)R\ (110\ ft/min)^2) \times (1\ ft/\ 12\ in.) \times (3600\ sec^2/min^2)$

Ar = 0.014

This shows that the thermal buoyant force is insignificant compared to the momentum force of the jet and that the buoyant force will not dominate the direction of the warm air leaving the blanket.

References:

1. HVAC Design Manual for Hospitals and Clinics, 2nd ed., 2013, Section 8.3.
2. Heat Transfer A Basic Approach, by M. Necati Ozisik, McGraw-Hill, 1985, p. 460.
3. ASHRAE Handbook of Fundamentals 2013, Ch. 20.

Exhibit E – Thomas Kuehn

Materials Considered

Plaintiffs' Expert Report of Michael W. Buck

Plaintiffs' Expert Report of Yadin David

Plaintiffs' Expert Report of Said Elghobashi

Plaintiffs' Expert Report of William Jarvis

Plaintiffs' Expert Report of Dan Koenigshofer

Plaintiffs' Expert Report of Dr. Johathan M. Samet

Plaintiffs' Expert Report of Dr. Michael J. Stonnington

3M 750, 4640927, I-52 #1 to #5_wt

3M750, 4640927, I52 #6 to #10_wt

3M.053.EDATA05

3M report RD-Test-PW-05-286536, dated 8/25/2016, by Winston Tan

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ASHRAE Handbook of Fundamentals 2013, Ch. 20.

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ASHRAE Standard 52.2 (2017)

ASHRAE D-90550 HVAC Design Manual for Hospitals and Clinics, 2nd ed.

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Deposition transcript of Karl Zgoda

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